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Recent searches for the radio lines of NH_3 in comets

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Abstract. Radio observations in the ammonia inversion lines of four comets, C/2001 A2 (LINEAR), 153P/Ikeya-Zhang, C/2001 Q4 (NEAT) and C/2002 T7 (LINEAR), were performed at the Effelsberg 100-m Radio Telescope during their respective close approaches to Earth. None of the four lowest energy metastable lines $(J,\ K = J)$, $J = 1$–4, could be detected in these comets. We derive the following 3σ upper bounds on the NH_3 production rate , and comparing to the corresponding water production rates, percentage NH_3 abundances relative to H_2O: $Q(NH_3) < 1.9 \times 10^{26}$ s^{-1} (0.63%) for C/2001 A2 (LINEAR), $Q(NH_3) < 2.7 \times 10^{26}$ s^{-1} (0.13%) for C/2001 Q4 (NEAT), $Q(NH_3) < 2.3 \times 10^{27}$ s^{-1} (0.74%) for C/2002 T7 (LINEAR) and $Q(NH_3) \leq 6.3 \times 10^{26}$ s^{-1} (0.63%) for Comet 153P/Ikeya-Zhang. At 0.74% or less, the ammonia-to-water ratios are factors of ~2 below the value for C/1995 O1 (Hale-Bopp) and 1P/Halley, suggesting chemical diversity between comets. The 18-cm lines of OH were clearly detected in the two comets observed during the 2004 campaign, thereby validating the cometary ephemerides.

Key words. comets: individual: comet C/2001 A2 (LINEAR), comet 153P/Ikeya-Zhang, comet C/2001 Q4 (NEAT), comet C/2002 T7 (LINEAR) – radio line: solar system

1. Introduction

Attempts to detect the radio K-band lines of ammonia (NH_3) were made during the recent apparitions of four comets with the 100-m Effelsberg Radio Telescope of the Max-Planck-Institut für Radioastronomie (MPIfR). Observations were performed on comets C/2001 A2 (LINEAR), 153P/Ikeya-Zhang, C/2001 Q4 (NEAT) and C/2002 T7 (LINEAR). A preliminary account of the observations of comets C/2001 A2 and 153P was previously published by Bird et al. (2002). Ammonia had previously been detected at MPIfR in the comets C/1983 H1 (IRAS-Araki-Alcock) (Altenhoff et al. 1983) and C/1995 O1 (Hale-Bopp) (Bird et al. 1997, 1999), and at the Green Bank Telescope in C/1996 B2 (Hyakutake) (Palmer et al. 1996). Column density predictions from model calculations were encouraging for these recent comets due to their relatively favorable viewing geometries.

Ammonia is expected to be among the more abundant volatile parent molecular constituents of cometary nuclei. Chemical models predict an abundance relative to H_2O ice of a few percent (Charnley & Rodgers 2002). Our observational knowledge about NH_3, ironically, comes largely from optical spectra of NH_2, its longer-lived dissociation product. A recent reanalysis of the NH_2 spectra of many comets suggests a typical NH_3 abundance of 0.5% (Kawakita & Watanabe 2002, using the comet database of Fink & Hicks 1996).

This is less than the estimates of 1.0–1.8% from the radio detections of NH_3 in C/1995 O1 (Hale-Bopp) (Bird et al. 1997, 2002; Hirota et al. 1999), but consistent with the revised estimate of 0.6% in C/1996 B2 (Hyakutake) (Bird et al. 1999). The NH_2 data imply an ammonia abundance of 0.75% for comet 1P/Halley, i.e. only about half the in situ value of 1.5% NH_3 measured during the flyby of the Giotto spacecraft (Meier et al. 1994).

In the interstellar medium, for comparison, the best estimates we have for the NH_3 abundance in ice are upper limits of 5% and 7% on the lines of sight towards W33A (Taban et al. 2003) and the massive protostars GL 989 and GL 2136 (Dartois et al. 2002), respectively.

Few radio spectra of NH_3 have been obtained because of the short photodissociation lifetime in the interplanary medium near 1 AU ($\tau \simeq 6000$ s). The diameter of the ammonia cloud around comets is typically only a few thousand kilometers and beam dilution can be significant. The radio line observations at MPIfR were thus scheduled near the relatively close approaches of the comets to Earth, thereby insuring that the source region of emission would be larger than, or at least only slightly smaller than, the 40″ MPIfR beam. Contrary to expectations, no NH_3 lines could be detected with certainty during the MPIfR comet observation campaigns in 2001–2004. The nondetections in C/2001 A2, 153P, C/2001 Q4 and C/2002 T7

Table 1. Orbital elements: MPIfR comet observation campaign 2001–2004.

Comet	C/2001 A2-B (LINEAR)	153P (Ikeya-Zhang)	C/2001 Q4 (NEAT)	C/2002 T7 (LINEAR)
Orb. element set [a]	2001-M48	2002-H05	2004-J69	2004-J05
Asc. node Ω (∘)	295.12564	93.37048	210.27852	94.85882
Arg. perih. ω (∘)	295.32853	93.37048	1.20653	157.73671
Inclination i (∘)	36.47538	28.12159	99.64258	160.658324
Perih. dist. q (AU)	0.7790280	0.5070583	0.9619575	0.6145967
Eccentricity e	0.9993455	0.9899505	1.0007438	1.0005157
Perih. epoch	2001 May 24.52062	2002 Mar. 18.97927	2004 May 15.96707	2004 Apr. 23.06172
Osc. epoch [b]	2001 May 11.0	2002 Mar. 27.0	2004 May 8.0	2004 Jun. 4.0

[a] Minor Planet Electronic Circular (MPEC) designation.
[b] Epoch of osculating elements.

Table 2. Mean observation parameters: MPIfR comet observation campaign 2001–2004.

Comet date	Δt [a] (min)	Elevation (∘)	RA_(J2000) (h mn)	_Dec (∘ ′)	Δ (AU)	r (AU)	∠SEC [b] (∘)	∠SCE [c] (∘)	d [d] (10^3 km)	$\Delta\theta$ [e] (10^3 km)	$\frac{d}{\Delta\theta}$ [e]
C/2001 A2-B (LINEAR) in 2001											
07.22 Jul.	70	43	23 31	05 37	0.262	1.130	109	58	9.7	7.9	1.22
153P/Ikeya-Zhang in 2002											
25.42 Apr.	53	57	20 50	61 29	0.409	0.974	74	83	9.5	12.3	0.77
04.40 May	83	58	18 19	55 30	0.410	1.124	95	63	11.8	12.3	0.96
06.38 May	17	51	17 55	52 38	0.416	1.157	100	59	12.3	12.5	0.98
07.41 May	45	54	17 43	51 14	0.421	1.174	102	57	12.6	12.7	0.99
C/2001 Q4 (NEAT) in 2004											
08.73 May	47	29	07 44	–07 53	0.327	0.970	74	87	9.3	9.9	0.94
13.69 May	90	53	08 23	+13 54	0.390	0.963	72	86	9.1	11.7	0.78
17.65 May	82	65	08 47	+25 42	0.473	0.962	70	82	9.1	14.3	0.64
C/2002 T7 (LINEAR) in 2004											
08.40 May	35	35	00 41	−4 06	0.534	0.699	41	109	5.4	16.1	0.34
13.44 May	63	28	01 43	−10 06	0.364	0.755	38	125	6.0	11.0	0.55

[a] Integration time on comet.
[b] Sun-Earth-Comet, solar elongation angle.
[c] Sun-Comet-Earth, phase angle.
[d] Estimated NH_3 coma diameter.
[e] MPIfR beam diameter (3 dB) at comet.

suggest an underabundance of NH_3 in these comets with respect to comet C/1995 O1 (Hale-Bopp) and 1P/Halley.

2. Ammonia line observations

The 18–26 GHz HEMT receiver system (primary focus) was used for this program. The lowest four inversion transitions of ammonia in its metastable states $(J, K = J)$, $J = 1$–4, were observed simultaneously in split-mode, dividing the autocorrelator into 4 bands with 2048 channels each. Raw spectra were recorded at a typical channel spacing of 0.25 km s^{-1} over the range of at least ±30 km s^{-1} about the expected line frequency at zero velocity in the comet rest frame. Spectra were calibrated using W3(OH) and system temperatures were generally between 35 and 60 K. Various observing modes were used: frequency switching (C/2001 A2), position switching every 30 s with a throw of either 5′ or 10′ (C/2001 A2, 153P), and beam switching using the rotating horn with a beam throw of 2′ and a 1s cycle (C/2001 Q4, C/2002 T7). Table 1 presents the orbital elements used to track the comet position and velocity.

A summary of the mean geometric parameters during the observations, including integration time Δt, geocentric distance Δ, and heliocentric distance r, is given in Table 2. This table also shows values for the estimated diameter of the NH_3 cloud, $d = \delta v \cdot \tau \cdot r^2$, with r the heliocentric distance (normalized to 1 AU), τ the mean lifetime of an ammonia molecule in interplanetary space, and δv the velocity spread of the coma gas assuming spherically symmetric outflow. The mean lifetime of an ammonia molecule in interplanetary space depends on the solar UV flux and is probably somewhat longer than average during the 2004 epoch near solar minimum. In the following we use values for the photodissociation lifetime of NH_3 at 1 AU in the range 5400 s $< \tau <$ 5800 s. Different values for the line width were taken for each individual comet: 1.4 km s^{-1} (C/2001 A2); 1.8 km s^{-1} (153P); 1.7 km s^{-1} (C/2001 Q4); and 1.9 km s^{-1} (C/2002 T7). These were selected on the basis of

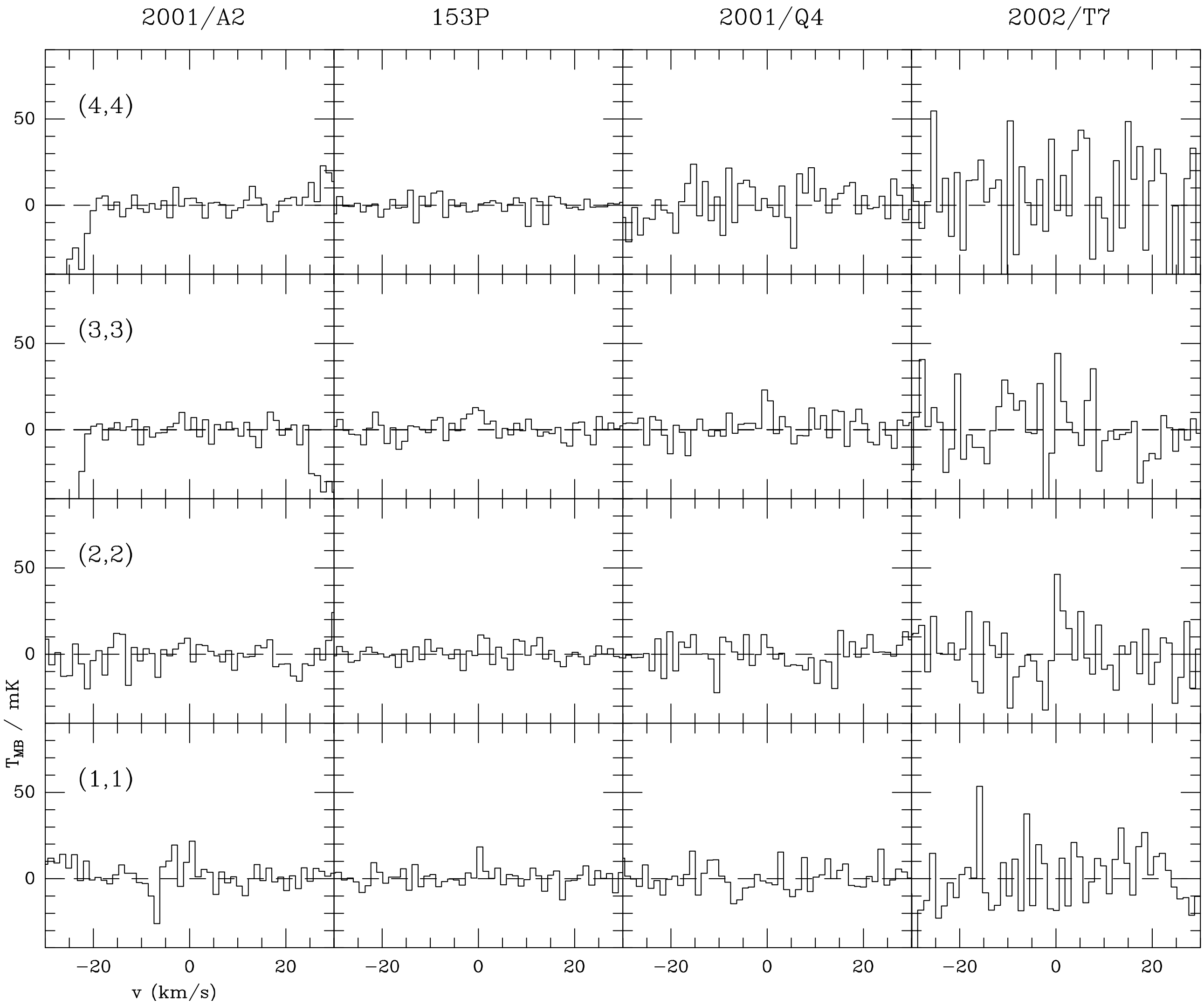

Fig. 1. NH_3 spectra of all comets (*left to right*: C/2001 A2, 153P, C/2001 Q4, C/2002 T7) in the lowest 4 metastable levels, centered at zero velocity in the comet rest frame.

independent radio line observations of other molecules during the same epoch (Biver et al., in preparation). The cloud diameter d may be compared to the next column, the physical extent of the FWHM antenna beam at MPIfR ($\Delta\theta$, with $\theta = 41.5''$) at the comet. The ratio of these quantities, $d/\Delta\theta$, is shown in the last column of Table 2. As a rule, the detection probablility is more favorable for large values of this ratio. The best conditions for this criterion held for comet C/2001 A2 and were still fairly good for comet 153P. The beam was distinctly larger than the ammonia cloud for most of the observations in 2004.

The Comet C/2001 A2 was observed to split into multiple nuclei (Sekanina et al. 2002). The position of the largest fragment (denoted "A2-B"), targeted for these observations, was derived from the then current ephemeris (orbital elements in MPEC 2001-M48). The initial observations of Comet 153P on 25 Apr. 2002, a long session in good weather, hinted at a marginal detection in the (1, 1) and (3, 3) lines (see Bird et al. 2002). Follow-up observations performed on 4, 6 and 7 May under less favorable weather conditions (and higher system noise temperatures), however, could not confirm the tentative ammonia lines. Comet C/2001 Q4 could not be observed at MPIfR until early May 2004 due to its high southern declination. The southward motion of Comet C/2002 T7 became problematic as it approached the Earth, thereby severely restricting the last observation interval. In fact, no NH_3 observations of Comet C/2002 T7 could be performed on 17 May 2004 due to lack of time following the OH observations (see next section). This and the unfavorable declination resulted in the shorter accumulated integration time.

The summed spectra for each ammonia line from all comet observations are displayed on the same scale (T_{MB} in mK over ± 30 km s^{-1}) in Fig. 1. The four spectra (from bottom to top) correspond to the (1, 1) to (4, 4) metastable states, and are centered at zero velocity in the comet rest frame.

Upper limits to the line amplitudes are estimated from the spectra by fitting a Gaussian line model. This is preferable to taking the 3σ upper limit from the rms noise level calculated over the whole spectrum because the actual data values in the central channels are taken into account. Therefore if there is any evidence for a weak line, that will increase our upper

Table 3. Ammonia line observations of comets at MPIfR and upper limits on the NH_3 column density.

Line (J,J)	Frequency	T_{rms} [mK]	$T_{99.7\%}$ [mK]	$[\int T_{MB}\,dv]_{max}$ [a] [mK km s^{-1}]	$\langle N(J,J)\rangle_{max}$ [b] [10^{12} cm^{-2}]	$n(J,J)$ [c]	$\langle N(NH_3)\rangle_{max}$ [10^{12} cm^{-2}]
Comet C/2001 A2-B (LINEAR): 7 Jul. 2001 (Δt = 70 min, δv = 1.4 km s^{-1})							
(1, 1)	23.69450	16	36	54	0.73	0.26	<2.8
(2, 2)	23.72263	16	30	45	0.46	0.18	<2.5
(3, 3)	23.87013	16	34	51	0.46	0.20	<2.3
(4, 4)	24.13942	15	30	45	0.38	0.05	<7.6
Lowest upper bound [d]							**<2.3**
Comet 153P/Ikeya-Zhang: 25 Apr. 2002 [e] (Δt = 53 min, δv = 1.8 km s^{-1})							
(1, 1)	23.69450	12	40	77	1.04	0.26	<4.0
(2, 2)	23.72263	15	26	50	0.51	0.18	<2.8
(3, 3)	23.87013	16	40	77	0.69	0.20	<3.5
(4, 4)	24.13942	14	14	27	0.23	0.05	<4.6
Lowest upper bound [d]							**<2.8**
Comet C/2001 Q4 (NEAT): 8, 13, 17 May 2004 (Δt = 219 min, δv = 1.7 km s^{-1})							
(1, 1)	23.69450	18	20	36	0.49	0.26	<1.9
(2, 2)	23.72263	19	28	51	0.52	0.18	<2.9
(3, 3)	23.87013	19	44	80	0.72	0.20	<3.6
(4, 4)	24.13942	23	20	36	0.31	0.05	<6.2
Lowest upper bound [d]							**<1.9**
Comet C/2002 T7 (LINEAR): 8, 13 May 2004 (Δt = 98 min, δv = 1.9 km s^{-1})							
(1, 1)	23.69450	29	30	61	0.82	0.26	<3.2
(2, 2)	23.72263	29	82	166	1.69	0.18	<9.4
(3, 3)	23.87013	29	52	105	0.95	0.20	<4.8
(4, 4)	24.13942	47	80	162	1.37	0.05	<27.4
Lowest upper bound [d]							**<3.2**

[a] $1.064 \cdot T_{99.7\%} \cdot \delta v$ with δv values as given in the table.
[b] From Eq. (1).
[c] Defined in Eq. (2).
[d] Lowest upper limit on $\langle N(NH_3)\rangle$ from the four lines observed.
[e] Calculations based on the best single epoch of observations.

limits on the line amplitudes accordingly, in order to definitely exclude the weak line. This was the case for Comet 153P/Ikeya-Zhang.

The model spectrum consists of a Gaussian line of amplitude A plus a baseline level B. The baseline level is considered again here as it is critical to the final line amplitudes, although linear baselines have already been subtracted from the spectra. The linewidth and line centre are fixed: the line centre always at 0 km s^{-1}, and the linewidth taken from the observed radio linewidths of other molecules (Biver et al., in preparation; see Table 3). A grid in parameter space is calculated for the line amplitude A and the baseline level B. We calculate the probability $P(A, B)$ that the line has an amplitude A with baseline B using a likelihood function $\exp(-\chi^2/2)$ with the constraint that A must be positive. As we are not interested in any residual baseline B, we integrate over B for each value of A to calculate the probability of each amplitude independent of baseline, $P(A) = \int P(A, B)\,dB \simeq \sum_{B_j} P(A_i, B_j)$. From $P(A)$ we identify the 99.7% upper limit on A (equivalent to 3σ for a normal distribution). The corresponding upper limit on the line integrated intensity is calculated from $1.064 \cdot A \cdot \delta v$. A summary of the NH_3 observations and derived results for all comets is given in Table 3.

3. Hydroxyl line observations

Following the nondetection of NH_3 lines during the observing sessions of Comets C/2001 Q4 and C/2002 T7 on 8 and 13 May 2004, it was decided to verify the telescope comet tracking configuration and, at the same time, the accuracy of the ephemerides. An imprompu change of receiver was requested and the initial hours of the final allocated observation interval on 17 May were devoted to observing the two strongest hyperfine transitions of the Λ-doublet ground-state of OH. The OH spectra recorded for each comet are shown in Fig. 2. The upper (lower) panels show the two strongest OH lines at 1667 (1665) MHz, centered at zero velocity in the rest frame of the comet ephemeris. The total integration

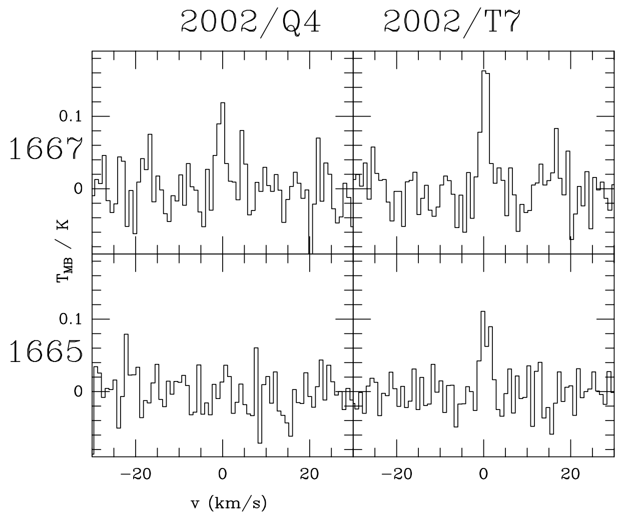

Fig. 2. OH radio line spectra recorded on 17 May 2004. *Left*: C/2001 Q4 (NEAT), 12 min integration time; *Right*: C/2002 T7 (LINEAR), 16 min integration time. The main beam brightness temperature T_{MB} is shown for the two OH lines at 1667 MHz (*upper*) and 1665 MHz (*lower*).

times, for comparison with the NH_3 observations, were only 12 and 16 min on the comets C/2001 Q4 and C/2002 T7, respectively.

A tabular summary of these observations, which were the first cometary OH-observations performed at MPIfR since Comet Halley (Bird et al. 1987), is given in Table 4. The intensity of the Λ-doublet lines is governed to a large extent by the inversion parameter, a measure of the imbalance in the upper and lower levels of the OH ground state (Schleicher & A'Hearn 1988). If the two levels are nearly equal, the inversion parameter is zero and the OH-maser is deactivated. Although this was very nearly the case for both comets on 17 May 2004, clear detections were obtained for all combinations except for comet C/2001 Q4 at 1665 MHz. The 1667 MHz line is about twice as strong as the 1665 MHz line in both comets, consistent with the 9:5 ratio expected under LTE conditions.

It was verified that the OH 1667 MHz line strengths were consistent with simultaneous measurements of the radio OH lines taken at the Nançay Radio Telescope (J. Crovisier, private communication, see Table 5). Note that the Nançay line strengths given in the table represent an average over the 1665 and 1667 MHz lines, both polarizations (LCP+RCP), and then scaled to the 1667 MHz line, assuming they conform to the LTE ratio. The line strengths at MPIfR were found to be somewhat higher than at Nançay, but are within the 1σ measurement errors. An exact agreement would not be expected as although the Nançay and MPIfR beams at 18 cm are similar in area, they are very different shapes and therefore couple to the comet OH emission differently (the Nançay beam is elongated with *FWHP* $3.5' \times 19'$, whereas the MPIfR beam is approximately round with a *FWHP* $7.8'$).

4. Upper limits on NH_3 column densities and production rates

Table 3 (Col. 6) shows the upper bounds on the column density $\langle N(J,J)\rangle_{\max}$ (in cm^{-2}) of molecules in the given state. These are calculated from the line integrated intensity in $K\,km\,s^{-1}$ using the expression (e.g., Rohlfs & Wilson 1996, p. 362)

$$\langle N(J,J)\rangle = 6.8\times 10^{12}\frac{J+1}{J}\left[\int T_{MB}(v)\mathrm{d}v\right]. \quad (1)$$

Both the upper and lower levels of the specific metastable NH_3 state are included in Eq. (1).

Knowing the mean column density of the NH_3 molecules in a given metastable state, the total column density of all NH_3 molecules is obtained from the relation

$$n(J,J) = \langle N(J,J)\rangle / \langle N(NH_3)\rangle \quad (2)$$

where $n(J,J)$, the relative population for each observed state, depends on the mean kinetic temperature and density of the cometary NH_3 gas in the antenna beam. The population will favor the metastable ($K = J$) states, particularly if the collision time is much longer than the decay time scales ~10 s for the nonmetastable states. We have performed statistical equilibrium calculations using collision rate coefficients of ammonia in an H_2 background gas (Danby et al. 1988, Schöier et al. 2005), but multiplied by a factor 4.3 to account roughly for the increase in cross section for collisions with H_2O. The larger mass of H_2O than H_2, which decreases the collision velocity, was not taken into account. The calculations included the lowest 17 states for ortho NH_3 up to (J.K) = (6, 0), 599 K above ground, and the lowest 24 states for para NH_3 up to (5, 1), 423 K above ground. The population of higher energy states was found to be negligible for densities up to 10^9 cm^{-3} and kinetic temperatures up to 200 K. The ortho-to-para ratio was assumed to be unity, but may, in fact, be slightly higher (Kawakita et al. 2001). The coma gas density for the observed comets, based on their later determined production rates, lie in the range from 10^5 to 10^6 cm^{-3} at a distance $R = 5000$ km from the nucleus. This can be taken as a typical mean density of the background gas in the telescope beam. The model calculations show that the NH_3 partition function in the coma is fairly insensitive to the actual density and only moderately dependent on the kinetic temperature over the range of plausible values from $50\ K \le T_k \le 100$ K. The calculated values of $n(J,J)$ in statistical equilibrium with $T_k = 100$ K are shown in Table 3 for each transition. The remaining column of Table 3 presents the total NH_3 column densities, $\langle N(NH_3)\rangle_{\max}$, calculated from Eq. (2) for the upper bounds of each transition and comet given in Table 3. To calculate the production rates, we use the strongest upper limits on $N(NH_3)$ from among the four individual NH_3 lines.

The upper bounds on the column densities for all observed comets are plotted in Fig. 3 and compared with pre-perihelion model predictions of $\langle N(NH_3)\rangle$ over an interval ±90 days about perihelion (curves). Figure 3 also shows the measurements and prediction curve for the firm detection of NH_3 in comet C/1995 O1 (Hale-Bopp) (solid black line and filled circles).

Table 4. OH line observations of comets at MPIfR, 17 May 2004.

Transition $F_u \rightarrow F_l$	Frequency [MHz]	T_{peak} [mK]	v_0 [km s^{-1}]	$FWHM = \delta v$ [km s^{-1}]	Line area [a] [mJy km s^{-1}]
Comet C/2001 Q4 (NEAT): 17 May 2004 (Δt = 12 min)					
$1 \rightarrow 1$	1665.4018	72 [b]	–	–	–
$2 \rightarrow 2$	1667.3590	119	–0.16 ± 0.26	2.06 ± 0.55	130 ± 31
Comet C/2002 T7 (LINEAR): 17 May 2004 (Δt = 16 min)					
$1 \rightarrow 1$	1665.4018	99	0.54 ± 0.23	2.69 ± 0.36	142 ± 23
$2 \rightarrow 2$	1667.3590	175	0.44 ± 0.22	2.18 ± 0.47	203 ± 39

[a] $\int T_{MB}\, dv$ (MPIfR gain: 2.0 K/Jy at 1665/1667 MHz).
[b] $T_{3\sigma}$.

Table 5. OH comet observations, Nançay RT and MPIfR, May 2004.

May date	Line area [a] LTE [mJy km s^{-1}]	Line area [b] LTE [mJy km s^{-1}]	Line area [c] 1667 only [mJy km s^{-1}]
Comet C/2001 Q4 (NEAT)			
16	104 ± 12	no obs.	no obs.
17	101 ± 12	65–207	130 ± 31
18	75 ± 12	no obs.	no obs.
Comet C/2002 T7 (LINEAR)			
16	176 ± 12	no obs.	no obs.
17	no obs.	229 ± 28	203 ± 39
18	185 ± 16	no obs.	no obs.

[a] Nançay RT, mean of 1665 MHz and 1667 MHz lines assuming LTE ratio of 5:9.
[b] MPIfR, mean of 1665 MHz and 1667 MHz lines assuming LTE ratio of 5:9. The range for C/2001 Q4 assuming the 1665 MHz line amplitude lies between 0 and its 3σ upper limit.
[c] MPIfR, 1667 MHz detection only.

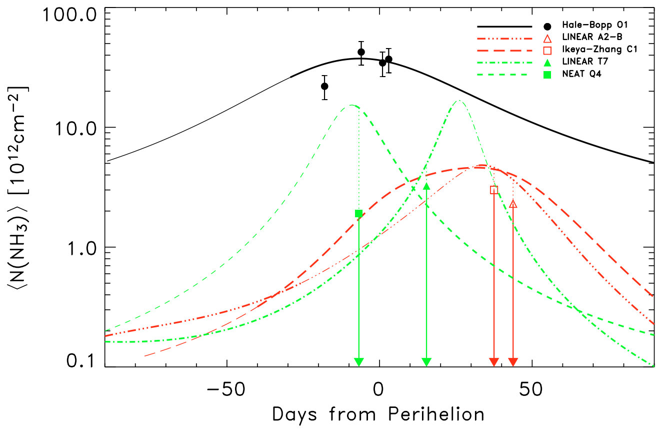

Fig. 3. Predicted and observed MPIfR beam-averaged NH_3 column densities for five comets. The thick part of the curves denote intervals where the declination enables observation at MPIfR ($\delta > -25°$). Maxima occur near closest approach to Earth. Points with standard deviations represent the line detections in C/1995 O1 (Hale-Bopp) (Bird et al. 1997); points without error bars are nondetection upper bounds for the Comets C/2001 A2-B, 153P, C/2001 Q4 and C/2002 T7. In all nondetection cases, the upper bounds are significantly less than the predictions based on an ammonia abundance of 1%. The shortfall is indicated in each case by the dotted line.

The model calculations assume that the ammonia production rate follows the water production rate with an abundance ratio of exactly 1.0%, a mean lifetime of $\tau \approx 5600$ s (with small corrections for the phase of the solar cycle), and an antenna beamwidth of $\theta = 41.5''$.

The H_2O production rate and gas outflow velocity for each comet were assumed to vary with heliocentric distance r (in AU) according to (e.g., A'Hearn et al. 1995):

$$Q(r) = Q_o \left[\frac{r_o}{r}\right]^{\alpha}; \quad \delta v(r) = \frac{\delta v_o}{\sqrt{r}} \tag{3}$$

with α (usually $\alpha \approx 3$) and the values of r_o, and Q_o taken from the literature. The linewidths at 1 AU (δv_o) are converted from the linewidths at each observation epoch (δv) given in Sect. 2. The model parameters and the reference sources used to calculate the prediction curves of Fig. 3 are listed in Table 6.

The unique stature of C/1995 O1 (Hale-Bopp), which had a production rate much greater than the other comets, is clearly evident in Fig. 3 and Table 6. The solid circle points with rms error bars for C/1995 O1 (Hale-Bopp) in Fig. 3 are derived from the measured (3, 3) line strengths (Bird et al. 1997). The water production rate at perihelion, 1.0×10^{31} s^{-1}, was taken from Colom et al. (1999).

The procedure originally developed by Snyder (1982) is used here to estimate the production rate $Q(S_i)$ of species i from the observed beam-averaged column density $\langle N(S_i)\rangle$

$$\langle N(S_i)\rangle = \frac{4Q(S_i)}{\pi\, \delta v\, \Delta\theta} \begin{cases} d/\Delta\theta & \text{for } d < \Delta\theta \\ \mathcal{F}(d/\Delta\theta) & \text{for } d > \Delta\theta \end{cases} \tag{4}$$

with d the comet coma diameter, Δ the geocentric distance, δv the linewidth (taken as $2u$, where u is the gas outflow velocity), and θ the half-power beam width of the antenna. The function $\mathcal{F}$, given by

$$\mathcal{F} = \arccos\left(\frac{\Delta\theta}{d}\right) + \frac{d}{\Delta\theta} - \sqrt{\left(\frac{d}{\Delta\theta}\right)^2 - 1} \tag{5}$$

varies from $\mathcal{F} = 1$ for $d = \Delta\theta$ to $\mathcal{F} = \pi/2$ for $d \gg \Delta\theta$.

Using Eq. (4), we can derive an upper bound on a comet's NH_3 production rate from the upper bounds on the column densities given in the bottom lines for each comet of Table 3. The resulting NH_3 production rates for these comets are given in Table 7 and range between 1.8 and 23×10^{26} s^{-1}.

Table 6. Comet production model parameters.

Comet	mm yyyy	Q_o [10^{29} s^{-1}]	r_o [AU]	δv_O [km s^{-1}]	α [s]	τ	Reference
C/1995 O1 (Hale-Bopp)	04 1997	100	0.914	1.8	3.0	5600	Colom et al. (1999)
C/2001 A2-B (LINEAR)	07 2001	0.28	1.130	1.49	3.0	5400	F. Bensch (priv. comm.)
153P/Ikeya-Zhang	04 2002	0.92	1.000	1.77	3.21	5600	Dello Russo et al. (2004)
C/2001 Q4 (NEAT)	05 2004	1.8	1.017	1.67	3.0	5800	N. Biver (priv. comm.)
C/2002 T7 (LINEAR)	05 2004	4.5	0.645	1.59	3.0	5800	N. Biver (priv. comm.)

Table 7. NH_3 production rates and abundances relative to H_2O.

Comet	Epoch	$Q(NH_3)$ [10^{26} s^{-1}]	$Q(H_2O)_r$ [10^{29} s^{-1}]	$[NH_3]/[H_2O]$
C/2001 A2-B (LINEAR)	7.22 Jul.	1.8	0.28	≤0.63%
153P/Ikeya-Zhang	25.42 Apr.	6.4	1.0	≤0.63%
C/2001 Q4 (NEAT)	14.11 May	2.7	2.1	≤0.13%
C/2002 T7 (LINEAR)	11.64 May	23	3.1	≤0.74%

5. Ammonia-to-water ratio

The strongly variable water production rate for Comet C/2001 A2-B was reported as $Q(H_2O) = 3.8 \times 10^{28}$ s^{-1} on 1.7–2.0 July 2001 (Biver et al. 2001), consistent also with $Q(H_2O) \sim 4.0 \times 10^{28}$ s^{-1} observed on 9–10 July 2001 (Dello Russo et al. 2005). The Odin satellite measured 5–8 × 10^{28} molec s^{-1} between 20 June 2001 and 7 July 2001 (Lecacheux et al. 2003). A recent compilation of continuous water production rates derived from SWAS observations (Submillimeter Wave Astronomy Satellite) of Comet C/2001 A2-B (F. Bensch, private communication) suggests a value of $Q(H_2O) = 2.8 \times 10^{28}$ s^{-1} as appropriate for the MPIfR observations on 7 July 2001. These water production rates imply that the maximum NH_3 fraction for the Comet C/2001 A2-B observations becomes 0.63%.

An estimate of the water production rate in Comet 153P/Ikeya-Zhang of $Q(H_2O) = 1.7 \times 10^{29}$ s^{-1} could be derived from Odin satellite observations of the 557 GHz line of water on 26.8 April 2002 (Crovisier et al., private communication; Lecacheux et al. 2003). HST ultraviolet OH observations on 20–22 April 2002 (Weaver et al., private communication) yielded $Q(H_2O) = 2.3 \times 10^{29}$ s^{-1}. Newer systematic estimates of the H_2O production for Comet 153P/Ikeya-Zhang (Dello Russo et al. 2004) are smaller by more than a factor of two with respect to the original estimates used in the NH_3 abundance estimates of Bird et al. (2002). The best fit model prediction of Dello Russo et al. (2004), the parameters of which are given in Table 6, yields a water production rate of $Q(H_2O) = 1.0 \times 10^{28}$ s^{-1} for the mean epoch of the MPIfR observations. We thus calculate an upper bound on the ammonia-to-water ratio in Comet 153P/Ikeya-Zhang of 0.63%.

Water production rates for the Comets C/2001 Q4 and C/2002 T7 have been reported (N. Biver, private communication) as $Q(H_2O) = 1.8 \pm 0.2 \times 10^{29}$ s^{-1} on 27.0 April 2004, and $Q(H_2O) = 4.5 \pm 1.0 \times 10^{29}$ s^{-1} on 2.0 May 2004, respectively. These lead to upper bounds on the ammonia fractional abundance relative to water of, respectively, 0.13% and 0.74%.

The upper limits for the relative NH_3 abundance in each comet, based on these H_2O production rates and the NH_3 production rates derived in Sect. 4, are presented in Table 7. For comparison, a summary of the ammonia abundance estimates from all previous comet observations has been compiled by Bockelée-Morvan et al. (2005).

All of the upper limits we present here are significantly lower than the estimate of 1.1% for C/1995 O1 (Hale-Bopp) (Bird et al. 1999) or 1.5% for Comet 1P/Halley (Meier et al. 1994). The relative abundance implied for C/2001 Q4 was found to be considerably lower than the values of 0.64–0.74% derived for the other three comets. This may be a real effect, but is subject to reconfirmation when finally agreed values for the water production rate become available.

6. Conclusions

Our observations suggest that there is a diversity of the NH_3 abundance among comets. This was already suggested by the large (more than a factor of ten) range of the NH/OH ratio observed from narrowband photometry in the visible for a large sample of comets by A'Hearn et al. (1995). The nondetections of ammonia in C/2001 A2-B (LINEAR), C/2001 Q4 (NEAT) and C/2002 T7 (LINEAR), as well as the very marginal detection in 153P/Ikeya-Zhang, lead to the preliminary indication that the NH_3 fraction may be a factor of ~2 lower than that derived from the detections in Comets 1P/Halley and C/1995 O1 (Hale-Bopp).

With the possible exception of C/2001 Q4 (NEAT), it is interesting that the upper limits all seem to be consistent with the 0.5% abundance determined from the NH_2 analysis of Kawakita & Watanabe (2002).

The accumulated statistical sample is clearly insufficient for drawing a final conclusion on the spread in relative abundances of NH_3 in cometary comae. Nevertheless, the current comet count does imply that the amount of ammonia in the archetypical comets 1P/Halley and C/1995 O1 (Hale-Bopp) may be the exception rather than the rule. Only more observations will provide final resolution of the issue.

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