Recent searches for the radio lines of NH$_3$ in comets

J. Hatchell$^{1,3}$, M. K. Bird$^2$, F. F. S. van der Tak$^1$, and W. A. Sherwood$^1$

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
2 Radioastronomisches Institut, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
3 School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK
e-mail: hatchell@astro.ex.ac.uk

Received 1 February 2005 / Accepted 9 May 2005

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 ($J = J = J$, $J = 1–4$), could be detected in these comets. We derive the following $3\sigma$ upper bounds on the NH$_3$ production rate, and comparing to the corresponding water production rates, percentage NH$_3$ abundances relative to H$_2$O: $Q$(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$_3$) $< 6.3 \times 10^{26}$ s$^{-1}$ (0.63%) for Comet 153P/Ikeya-Zhang. At 0.74% or less, the ammonia-to-water ratios are factors of $\sim 2$ 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$_2$O of a few percent (Charnley & Rodgers 2002). Our observational knowledge about NH$_3$, ironically, comes largely from optical spectra of NH$_3$, 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 interplanetary medium near 1 AU ($\tau \approx 6000$ 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$\arcsec$ 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
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 $0.25 \text{ km s}^{-1}$ over the range of at least $\pm 30 \text{ km s}^{-1}$ 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 $5^\prime$ or $10^\prime$ (C/2001 A2, 153P), and beam switching using the rotating horn with a beam throw of $2^\text{h}$ and a 1 s 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 $\Delta t$, geocentric distance $\Delta$, and heliocentric distance $r$, is given in Table 2. This table also shows values for the estimated diameter of the NH$_3$ coma, $d$ (10$^2$ km), and the mean lifetime of an ammonia molecule in interplanetary space, $\tau$, with $r$ the heliocentric distance (normalized to 1 AU), $\delta v$ 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$_3$ 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.

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 | 2001-M48 | 2002-H05 | 2004-J69 | 2004-J05 |
| Asc. node $\Omega$ ($\circ$) | 295.12564 | 93.37048 | 210.27852 | 94.85882 |
| Arg. perih. $\omega$ ($\circ$) | 295.32853 | 93.37048 | 1.20653 | 157.73671 |
| Inclination $i$ ($\circ$) | 36.47538 | 28.12159 | 99.64258 | 160.65832 |
| 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 82 | 2002 Mar. 18 | 2004 May 15 | 2004 Apr. 23 |
| Osc. epoch a | 2001 May 11.0 | 2002 Mar. 27.0 | 2004 May 8.0 | 2004 Jun. 4.0 |

* Minor Planet Electronic Circular (MPEC) designation.
* Epoch of osculating elements.

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

| Comet          | $\Delta t$ ($\text{min}$) | Elevation RA ($\text{h m n}$) | RA$_{(2000)}$ Dec ($\circ$) | $\Delta$ (AU) | $r$ (AU) | $\delta v$ (10$^2$ km) | $\Delta \theta$ (10$^2$ km) | $\Delta t$ ($\text{min}$) |
|----------------|--------------------------|-----------------------------|-------------------|--------------|---------|-------------------|-------------------|---------|
| C/2001 A2-B (LINEAR) in 2001 | 70 | 43 | 23 31 | 05 37 | 0.262 | 1.130 | 109 | 9.7 | 7.9 | 1.22 |
| 153P/Ikeya-Zhang in 2002 | 53 | 57 | 20 50 | 61 29 | 0.409 | 0.974 | 74 | 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 |
| 05.38 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 | 70 | 47 | 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 | 35 | 35 | 00 41 | 04 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 |

* Integration time on comet.
* Sun-Earth-Comet, solar elongation angle.
* Sun-Comet-Earth, phase angle.
* Estimated NH$_3$ coma diameter.
* MPIfR beam diameter (3 dB) at comet.
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 probability 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 \( \text{NH}_3 \) 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 (\( T_{\text{MB}} \) in mK over \( \pm 30 \text{ km s}^{-1} \)) 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.

**Fig. 1.** \( \text{NH}_3 \) 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.
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, \( P(A) = \int P(A, B) dB \geq \sum_B P(A, B) \). From \( P(A) \) we identify the 99.7% upper limit on \( A \) (equivalent to 3\( \sigma \) 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 \( \text{NH}_3 \) observations and derived results for all comets is given in Table 3.

### 3. Hydroxyl line observations

Following the nondetection of \( \text{NH}_3 \) 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 impromptu 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 \( 1 \)\( \cdot \)\( 0 \) ground-state of \( \text{OH} \). The \( \text{OH} \) spectra recorded for each comet are shown in Fig. 2. The upper (lower) panels show the two strongest \( \text{OH} \) lines at 1667 (1665) MHz, centered at zero velocity in the rest frame of the comet ephemeris. The total integration
column densities \( \langle N(J, J) \rangle_{\text{max}} \) (in \( \text{cm}^{-2} \)) of molecules in the given state. These are calculated from the line integrated intensity in \( \text{K} \text{km s}^{-1} \) using the expression (e.g., Rohlfs & Wilson 1996, p. 362)

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

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

\[
m(J, J) = \langle N(J, J) \rangle / \langle N(\text{NH}_3) \rangle
\]

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 \( \sim 10 \text{ s} \) 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\(_2\)O. The larger mass of H\(_2\)O 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 (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 \( 10^9 \text{ cm}^{-3} \) 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 \( 10^6 \text{ cm}^{-3} \) at a distance \( R = 5000 \text{ km} \) 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 \( \leq T_k \leq 100 \text{ K} \). The calculated values of \( n(J, J) \) in statistical equilibrium with \( T_k = 100 \text{ K} \) are shown in Table 3 for each transition. The remaining column of Table 3 presents the total NH\(_3\) column densities, \( \langle N(\text{NH}_3) \rangle_{\text{max}} \), 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 \( N(\text{NH}_3) \) 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 \( \langle N(\text{NH}_3) \rangle \) over an interval \( \pm 90 \text{ days} \) 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 | Frequency | $T_{peak}$ | $\delta v$ | FWHM | Line area $^a$ |
|------------|-----------|------------|------------|-------|---------------|
| $F_a \rightarrow F_I$ | MHz | [mK] | [km s$^{-1}$] | [km s$^{-1}$] | [mJy km s$^{-1}$] |
| Comet C/2001 Q4 (NEAT); 17 May 2004 ($\Delta t = 12$ min) | | | | | |
| 1$\rightarrow$1 1665.4018 | 72$^b$ | – | – | – |
| 2$\rightarrow$2 1667.3590 | 119 | –0.16 $\pm$ 0.26 | 2.06 $\pm$ 0.55 | 130 $\pm$ 31 |
| Comet C/2002 T7 (LINEAR); 17 May 2004 ($\Delta t = 16$ min) | | | | | |
| 1$\rightarrow$1 1665.4018 | 99 | 0.54 $\pm$ 0.23 | 2.69 $\pm$ 0.36 | 142 $\pm$ 23 |
| 2$\rightarrow$2 1667.3590 | 175 | 0.44 $\pm$ 0.22 | 2.18 $\pm$ 0.47 | 203 $\pm$ 39 |

$^a$ $\int T_{bol} \, d\nu$ (MPIfR gain: 2.0 K/Jy at 1665/1667 MHz).

$^b$ $T_{36}$. 

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

| May date | Line area $^a$ [mJy km s$^{-1}$] | Line area $^b$ [mJy km s$^{-1}$] | Line area $^c$ [mJy km s$^{-1}$] |
|----------|-------------------------------|-------------------------------|-------------------------------|
| Comet C/2001 Q4 (NEAT) | | | |
| 16 | 104 $\pm$ 12 | no obs. | no obs. |
| 17 | 101 $\pm$ 12 | 65–207 | 130 $\pm$ 31 |
| 18 | 75 $\pm$ 12 | no obs. | no obs. |
| Comet C/2002 T7 (LINEAR) | | | |
| 16 | 176 $\pm$ 12 | no obs. | no obs. |
| 17 | no obs. | 229 $\pm$ 28 | 203 $\pm$ 39 |
| 18 | 185 $\pm$ 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 3$\sigma$ upper limit.

$^c$ MPIfR, 1667 MHz detection only.

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 $\tau = 5600$ s (with small corrections for the phase of the solar cycle), and an antenna beamwidth of $\theta = 41.5^\circ$.

The H$_2$O 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):

$$Q(r) = Q_{o} \left(\frac{r_{o}}{r}\right)^{a}; \quad \delta v(r) = \frac{\delta v_{o}}{\sqrt{F}}$$

(3)

with $a$ (usually $a \approx 3$) and the values of $r_{o}$, and $Q_{o}$ taken from the literature. The linewidths at 1 AU ($\delta v_{o}$) are converted from the linewidths at each observation epoch ($\delta v$) 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, $1.0 \times 10^{31} \, s^{-1}$, 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 $N(S_i)$

$$\langle N(S_i) \rangle = \frac{4Q(S_i)}{\pi \delta v \Delta \theta} \frac{d}{d \Delta \theta} \left( F \frac{d}{d \Delta \theta} \right) \text{for } d < \Delta \theta$$

$$= \frac{d}{d \Delta \theta} \text{for } d > \Delta \theta$$

(4)

with $d$ the comet coma diameter, $\Delta$ the geocentric distance, $\delta v$ the linewidth (taken as $2\sigma$, where $\sigma$ is the gas outflow velocity), and $\theta$ the half-power beam width of the antenna. The function $F$, given by

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

(5)

varies from $F = 1$ for $d = \Delta \theta$ to $F = \pi/2$ 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 $23 \times 10^{26} \, s^{-1}$.
Table 6. Comet production model parameters.

| Comet                      | mm yyyy | $Q_o$  | $r_o$  | $\delta v_o$ | $\alpha$ | $\tau$ | 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$_2$O.

| Comet                      | Epoch       | $Q$(NH$_3$) | $Q$(H$_2$O)$_r$ | [NH$_3$]/[H$_2$O] |
|----------------------------|-------------|-------------|-----------------|-------------------|
| 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$_2$O) = 3.8 × 10$^{28}$ s$^{-1}$ on 1.7–2.0 July 2001 (Biver et al. 2001), consistent also with $Q$(H$_2$O) ~ 4.0 × 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$_2$O) = 2.8 × 10$^{28}$ s$^{-1}$ as appropriate for the MPIIR 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$_2$O) = 1.7 × 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$_2$O) = 2.3 × 10$^{29}$ s$^{-1}$. Newer systematic estimates of the H$_2$O 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$_2$O) = 1.0 × 10$^{28}$ s$^{-1}$ for the mean epoch of the MPIIR 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$_2$O) = 1.8 ± 0.2 × 10$^{29}$ s$^{-1}$ on 27.0 April 2004, and $Q$(H$_2$O) = 4.5 ± 1.0 × 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$_2$O 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 NHOH 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.
Acknowledgements. The results reported in this work are based on observations made with the 100-m telescope of the Max-Planck-Institut für Radioastronomie (MPIfR) at Effelsberg. We are grateful to W. J. Altenhoff for carefully preparing the cometary ephemerides and to K. M. Menten for discussions and helping to arrange for these observations. We thank N. Biver and F. Bensch for providing preliminary water production rates for the comets C/2001 Q4 (NEAT)/C/2002 T7 (LINEAR) and C/2001 A2 (LINEAR), respectively, and J. Crovisier for his helpful comments as referee, and for kindly providing the OH line strengths observed at the Nançay RT and the linewidths derived from other molecular observations in advance of publication.

References

A'Hearn, M. F., Millis, R. L., Schleicher, D. G., Osip, D. J., & Birch, P. V. 1995, Icarus, 118, 223
Altenhoff, W. J., Batrla, W., Huchtmeier, W. K., et al. 1983, A&A, 125, L19
Bird, M. K., Huchtmeier, W. K., von Kap-herr, A., et al. 1987, in Cometary Radio Astronomy, ed. W. M. Irvine, et al., Proc. NRAO Workshop, 17, 85
Bird, M. K., Huchtmeier, W. K., Gensheimer, P., et al. 1997, A&A, 325, L5
Bird, M. K., Janardhan, P., Wilson, T. L., et al. 1999, Earth, Moon & Planets, 78, 21
Bird, M. K., Hatchell, J., van der Tak, F. F. S., Crovisier, J., & Bockelée-Morvan, D. 2002, in Proc. Asteroids, Comets, Meteors (ACM 2002), Berlin 2002, ed. B. Warmbein, ESA SP-500, 697
Biver, N., Lecacheux, A., Crovisier, J., et al. 2001, BAAS, 33, 1121
Bockelée-Morvan, D., Crovisier, J., Mumma, M. J., & Weaver, H. A. 2005, Comets II, in press

Charnley, S. B., & Rodgers, S. D. 2002, ApJ, 569, L133
Colom, P., Gérard, E., Crovisier, J., et al. 1999, Earth, Moon & Planets, 78, 37
Crovisier, J., Biver, N., Moreno, R., et al. 2001, BAAS, 33, 1121
Danby, G., Flower, D. R., Valiron, P., Schilke, P., & Walmsley, C. M. 1988, MNRAS, 235, 229
Dartois, E., d'Hendecourt, L., Thi, W., Pontoppidan, K. M., & van Dishoeck, E. F. 2002, A&A, 394, 1057
Dello Russo, N., DiSanti, M. A., Magee-Sauer, K., et al. 2004, Icarus, 168, 186
Dello Russo, N., Bonev, B. P., DiSanti, M. A., et al. 2005, ApJ, 621, 537
Fink, U., & Hicks, M. D. 1996, ApJ, 459, 729
Hirota, T., Yamamoto, S., Kawaguchi, K., Sakamoto, A., & Ukita, N. 1999, ApJ, 520, 895
Kawakita, H., Watanabe, J., Ando, H., et al. 2001, Science, 294, 1089
Kawakita, H., & Watanabe, J. 2002, ApJ, L177
Lecacheux, A., Biver, N., Grovisier, J., et al. 2003, A&A, 402, L55
Meier, R., Eberhardt, P., Krankowsky, D., & Hodges, R. R. 1994, A&A, 287, 268
Palmer, P., Wootten, A., Butler, B., et al. 1996, BAAS, 28, 927
Rohlfs, K., & Wilson, T. L. 1996 (Berlin: Springer-Verlag)
Schleicher, D. G., & A'Hearn, M. F. 1988, ApJ, 331, 1058
Schöier, F. L., van der Tak, F. F. S., van Dishoeck, E. F., & Black, J. H. 2005, A&A, 432, 369, http://www.strw.leidenuniv.nl/~moldata/
Sekanina, Z., Jehin, E., & Boehnhardt, H. 2002, ApJ, 572, 679
Snyder, L. E. 1982, Icarus, 51, 1
Taban, I. M., Schutte, W. A., Pontoppidan, K. M., & van Dishoeck, E. F. 2003, A&A, 399, 169