Ammonia and other parent molecules in comet 10P/Tempel 2 from Herschel/HIFI* and ground-based radio observations

N. Biver1, J. Crovisier1, D. Bockelée-Morvan1, S. Szutowicz2, D. C. Lis3, P. Hartogh4, M. de Val-Borro4, R. Moreno1, J. Boissier3,6, M. Kidger7, M. Küppers7, G. Paubert8, N. Dello Russo9, R. Vervack9, H. Weaver9, and HssO team

1 LESIA, Observatoire de Paris, CNRS, UPMC, Université Paris-Diderot, 5 place Jules Janssen, 92195 Meudon, France
E-mail: Nicolas.Biver@obspm.fr
2 Space Research Centre, PAS, Warszawa, Poland
3 Caltech, Pasadena, CA, USA
4 Max Planck Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany
5 Istituto di Radioastronomia – INAF, Bologna, Italy
6 ESO, Garching bei München, Germany
7 ESAC, Villafranca del Castillo, Spain
8 IRAM, Avd. Divina Pastora, 7, 18012 Granada, Spain
9 JHU/APL, Laurel, Maryland, USA

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ABSTRACT

The Jupiter-family comet 10P/Tempel 2 was observed during its 2010 return with the Herschel Space Observatory. We present here the observation of the Jk (1-0) transition of NH3 at 572 GHz in this comet with the Heterodyne Instrument for the Far Infrared (HIFI) of Herschel. We also report on radio observations of other molecules (HCN, CH3OH, H2S and CS) obtained during the 1999 return of the comet with the CSO telescope and the JCMT, and during its 2010 return with the IRAM 30-m telescope. Molecular abundances relative to water are 0.09%, 1.8%, 0.4%, and 0.08% for HCN, CH3OH, H2S, and CS, respectively. An abundance of 0.5% for NH3 is obtained, which is similar to the values measured in other comets. The hyperfine structure of the ammonia line is resolved for the first time in an astronomical source. Strong anisotropy in the outgassing is present in all observations from 1999 to 2010 and is modelled to derive the production rates.

Key words. techniques: spectroscopic – submillimeter: planetary systems – radio lines: planetary systems – comets: individual: 10P/Tempel 2

1. Introduction

With an abundance of ≈0.5% relative to water, ammonia is a major repository of nitrogen in cometary volatiles (Bockelée-Morvan et al. 2004). The photodissociation products of NH3, NH2 and NH are routinely observed in the visible spectra of comets (Feldman et al. 2004). The direct observation of ammonia is difficult because it is a short-lived molecule (lifetime ≈5000 s at 1 AU from the Sun) and because its lines are either weak or affected by telluric absorption.

In previous radio observations of NH3, the inversion transitions near 24 GHz were tentatively detected with ground-based radio telescopes in C/1983 H1 (IRAS-Araki-Alcock) (Attenhoff et al. 1983), but not in IRP/Halley (Bird et al. 1987). They were then definitely detected in C/1996 B2 (Hyakutake) (Palmer et al. 1996) and C/1995 O1 (Hale-Bopp) (Bird et al. 1997; Hirota et al. 1999) and tentatively detected in 153P/Ikeya-Zhang (Bird et al. 2002; Hatchell et al. 2005).

Ammonia rotational lines are expected to be much stronger, but they fall in the submillimetric spectral range and have to be observed from space. The Jk (1-0) line at 572.5 GHz was first detected in C/2001 Q4 (NEAT) and C/2002 T7 (LINEAR) with the Odin satellite (Biver et al. 2007).

Ammonia was also observed from its ν1 and/or ν3 vibrational bands near 3 μm in comets 6P/d’Arrest, 73P/Schwassmann-Wachmann 3, C/1995 O1 (Hale-Bopp), C/2002 T7 (LINEAR), C/2004 Q2 (Machholz), C/2006 P1 (McNaught), and 103P/Hartley 2 (Kawakita & Mumma 2011, and references therein).

Comet 10P/Tempel 2 is a Jupiter-family comet discovered in 1873 by Wilhelm Tempel. Its orbital period is 5.5 years; thus alternate perihelion passages are favourable. Its behaviour has already been well documented, 2010 being the year of the 22nd return to perihelion observed for this comet. Prior to 1994, its perihelion distance was shorter (∼1.31–1.39 AU vs. 1.48 AU), resulting in a closer approach to the Earth and the comet being more active at perihelion. After the 1999 apparition, the orbit of the comet slightly changed and the perihelion distance decreased again to 1.42 AU.

Comet 10P/Tempel 2 has a relatively large nucleus (∼16 × 8 km; Jewitt & Luu 1989; Lamy et al. 2009), and a well-studied rotation period of ∼8.95 h, found to be increasing with time (Knight et al. 2011). Given its relatively low outgassing rate, only a small fraction of its nucleus is active. Strong seasonal effects are observed: the activity rises very rapidly during the last three months before perihelion and peaks about one month after. A prominent dust jet close to the north pole has been observed in images at each perihelion.
Table 1. Molecular observations in comet 10P/Temps 2.

| UT date | (r_h) [AU] | (r_D) [AU] | Integ. time [min]^a | Line | Intensity [K km s^{-1}] | Velocity shift [km s^{-1}] | Prod. rate [mol s^{-1}] |
|---------|------------|------------|---------------------|------|-------------------------|--------------------------|--------------------------|
| 1999 perihelion passage: | | | | | | | |
| JCMT 09/04.2–06.3 | 1.482 | 0.816 | 157 | HCN(4–3) | 0.058 ± 0.012 | -0.86 ± 0.23 | 0.5 ± 0.1 × 10^{25} |
| CSO 09/11.2–12.3 | 1.482 | 0.851 | 133 | HCN(3–2) | 0.106 ± 0.012 | -0.20 ± 0.08 | 1.4 ± 0.2 × 10^{25} |
| CSO 09/12.32 | 1.482 | 0.855 | 72 | CH_{3}OH(4_{1–4_{0}}A–+) | 0.080 ± 0.018 | +0.19 ± 0.15 | 3.7 ± 1.0 × 10^{26} |
| JCMT 10/01.3–02.3 | 1.500 | 0.980 | 67 | HCN(3–2) | 0.090 ± 0.019 | -0.57 ± 0.18 | 0.9 ± 0.2 × 10^{25} |

2010 perihelion passage:

| IRAM 07/07.28 | 1.423 | 0.745 | 126 | HCN(1–0) | 0.057 ± 0.013 | -0.16 ± 0.16 | 1.6 ± 0.4 × 10^{25} |
| IRAM 07/08.26 | 1.423 | 0.742 | 131 | HCN(1–0) | 0.054 ± 0.009 | -0.44 ± 0.14 | 1.5 ± 0.2 × 10^{25} |
| IRAM 07/10.22 | 1.424 | 0.734 | 103 | HCN(3–2) | 0.410 ± 0.033 | -0.30 ± 0.05 | 1.5 ± 0.1 × 10^{25} |
| IRAM 07/10.34 | 1.424 | 0.734 | 42 | HCN(1–0) | 0.044 ± 0.016 | -0.65 ± 0.33 | 1.2 ± 0.4 × 10^{25} |
| IRAM 07/11.17 | 1.424 | 0.731 | 61 | HCN(3–2) | 0.427 ± 0.036 | -0.41 ± 0.05 | 1.6 ± 0.2 × 10^{25} |
| IRAM 07/11.28 | 1.424 | 0.731 | 131 | HCN(1–0) | 0.068 ± 0.010 | -0.49 ± 0.13 | 1.8 ± 0.3 × 10^{25} |
| IRAM 07/07.2–08.4 | 1.423 | 0.743 | 257 | CH_{3}OH(1_{0}–1_{0},E) | 0.028 ± 0.010 | | |
| | | | | | | | |
| IRAM 07/11.26 | 1.424 | 0.731 | 98 | CH_{3}OH(2_{0}–2_{0},E) | 0.044 ± 0.010 | | |
| | | | | | | | |
| IRAM 07/10.34 | 1.424 | 0.734 | 42 | CH_{3}OH(3_{3}–3_{3},E) | 0.032 ± 0.010 | | |
| IRAM 07/11.34 | 1.424 | 0.730 | 33 | CH_{3}OH(4_{0}–4_{0},E) | 0.050 ± 0.010 | -0.41 ± 0.10 &times; 10^{-6} | 3.2 ± 0.8 × 10^{26} |
| IRAM 07/11.34 | 1.424 | 0.730 | 33 | CH_{3}OH(3_{3}–3_{3},E) | 0.050 ± 0.010 | | |
| HIFI 07/18.9–19.3 | 1.431 | 0.708 | 54 | CH_{3}OH(4_{0}–4_{0},E) | 0.041 ± 0.008 | -0.42 ± 0.08 &times; 10^{-6} | 3.2 ± 0.4 × 10^{26} |
| HIFI 07/18.9–19.3 | 1.431 | 0.708 | 54 | CH_{3}OH(3_{3}–3_{3},E) | 0.030 ± 0.008 | | |
| HIFI 07/18.9–19.3 | 1.431 | 0.708 | 54 | CH_{3}OH(2_{0}–2_{0},E) | 0.046 ± 0.008 | | |
| HIFI 07/18.9–19.3 | 1.431 | 0.708 | 54 | H_{2}O(1_{0}–1_{0}) | 0.065 ± 0.021 | -0.43 ± 0.26 | 7.1 ± 2.3 × 10^{26} |
| HIFI 07/18.9–19.3 | 1.431 | 0.708 | 54 | NH_{3}(1_{0}–1_{0}) | 0.049 ± 0.011 | -0.02 ± 0.14 | 1.5 ± 0.3 × 10^{25} |
| HIFI 07/18.9–19.3 | 1.431 | 0.708 | 54 | CH_{3}CN(8_{1}–7_{0}) | 0.011 ± 0.008 | <0.062 | <0.8 × 10^{23} |

Notes. (a) Total integration time, ON+OFF or ON in frequency switching mode (JCMT and HIFI); (b) reference line frequencies (excepted for NH_{3} – see text) were taken from CDMS (Müller et al. 2005); (c) value based on the average of the 6 strongest lines; (d) sum of the three transitions Jx = 8_{0}–7_{0}, 8_{1}–7_{1}, and 8_{2}–7_{2}; (e) Doppler shift measured with respect to the barycentric position of the hyperfine structure of the line at 572.498.160 MHz.

We report on an observation of the 572.5 GHz line of ammonia in comet 10P/Temps 2, which was part of the study of this comet with the Herschel Space Observatory. Preliminary reports were given by Biver et al. (2010) and Szutowicz et al. (2011). Additional analyses of the observations of water with the Heterodyne Instrument for the Far Infrared (HIFI) in this comet will be presented by Szutowicz et al. (in prep.). Several water lines were also detected with the Photodetector Array Camera and Spectrometer (PACS) and the Spectral and Photometric Imaging REceiver (SPIRE) instruments of Herschel and will be presented in a future paper.

In support of Herschel observations, 10P/Temps 2 was observed from the ground at millimetric wavelengths with the Institut de radioastronomie millimétrique (IRAM) 30-m telescope. We also present observations obtained at the antipetunélite perihelion passage (1999), with the Caltech Sumillator Observatory (CSO) telescope and the James Clerk Maxwell Telescope (JCMT), which helped to prepare the Herschel observations.

2. Observations

The 1999 perihelion of comet 10P/Temps 2 was on 8 September at r_h = 1.48 AU. The perigee took place on 12 July at 0.65 AU. HCN was observed at JCMT on 4 and 6 September, and again on 1 and 2 October. HCN was also observed at CSO on 11 and 12 September (Fig. 3) and CH_{3}OH on the 12th only.

The 2010 perihelion was on 4 July at r_h = 1.42 AU and perigee took place on 26 August at Δ = 0.65 AU. The comet was observed with the IRAM 30-m radio-telescope between 7.2 and 11.4 July 2010 UT. The first two nights suffered from bad weather and the third was completely lost, but days 4 and 5 yielded good data (Figs. 4–6). Table 1 provides the list of detected lines.

Comet 10P was also observed in 2010 with the Herschel Space Observatory (Pilbratt et al. 2010) using HIFI (de Graauw et al. 2010), within the framework of the Water and related chemistry in the Solar System (H harmed) project (Hartog et al. 2009). Several water rotational lines were observed and mapped from 15 June to 29 July 2010 (Szutowicz et al. 2011 and in prep.). The observation of ammonia took place on 19.1 July 2010 UT when the comet was at r_h = 1.43 AU and at Δ = 0.71 AU from Herschel. The Jx(1_{0}–0_{0}) transition of NH_{3} at 572.5 GHz and the 1_{0}–1_{0} line of H_{2}O at 557 GHz were observed simultaneously in the frequency-switching mode, the former in the upper side band and the latter in the lower side band of the band 1b receiver of HIFI. A total of 54 min of integration time were spent on the comet, split into five observations
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Fig. 1. Water H$_2$O (1$_{10}$–1$_{01}$) line observed in comet 10P/Tempel 2 with Herschel using the HRS on 19 July 2010.

Fig. 2. Ammonia $J_K (10–00)$ line observed in comet 10P/Tempel 2 with Herschel using the HRS on 19 July 2010. The position and relative intensities of the hyperfine components are shown with a synthetic spectrum overplotted that takes into account hyperfine structure and asymmetric outgassing (see text).

Fig. 3. HCN $J(3–2)$ line at 265.886 GHz observed in comet 10P/Tempel 2 with the CSO on 11–12 September 1999. The positions and relative intensities of the hyperfine components are drawn as detailed in Fig. 4.

Fig. 4. HCN $J(3–2)$ line at 265.886 GHz observed in comet 10P/Tempel 2 with the IRAM 30-m telescope on 10–11 July 2010. The position and relative intensities of the hyperfine components are shown and a synthetic spectrum including asymmetric outgassing (see text) and hyperfine structure is overplotted.

Fig. 5. HCN $J(1–0)$ line at 88.632 GHz observed in comet 10P/Tempel 2 with the IRAM 30-m telescope on 7–11 July 2010. The position and relative intensities of the hyperfine components are shown and a synthetic spectrum considering asymmetric outgassing (see text) is overplotted.

Fig. 6. CH$_3$OH lines at 157 GHz observed in comet 10P/Tempel 2 with the IRAM 30-m telescope on 11 July 2010.

3. Results

3.1. Modelling the data

The same excitation and outgassing pattern model has been used to analyse all data. The density distribution is based on the Haser model, with photodissociation rates at 1 AU, $\beta_0 \approx 1.88 \times 10^{-5}$ s$^{-1}$ in 1999 and $\beta_0 = 1.60 \times 10^{-5}$ s$^{-1}$ in 2010, for HCN, based on the solar activity. The gas temperature is constrained by the rotational temperature of methanol lines and the outgassing pattern and expansion velocity are constrained by the line shapes. Collisions with electrons are taken into account as modelled in Zakharov et al. (2007) with a density scaling factor $x_{\text{ee}}$ of 0.5 (Biver et al. 2006).

All lines (Figs. 3–5) show a strong asymmetry (mean Doppler shift around −0.3 to −0.4 km s$^{-1}$, Table 1) and need to
be modelled with asymmetric outgassing. The strong blueshift and a phase angle (≈42°) smaller than 90° suggest that a large part of the outgassing is dominated by a relatively narrow jet on the day-side that is not far from the direction to the Earth. The opening of the jet and the fraction of outgassing it contains were constrained by the Doppler shifts of the lines and optimized to fit the line shapes. The half width at half maximum (HWHM) of the lines on the negative and positive sides suggests expansion velocities of 0.9 and 0.5 km s\(^{-1}\) on the day and night sides, respectively.

The rotational temperature of methanol was found to be 16 ± 7 K, 32 ± 8, and 25 ± 4 K on 7–8 September 1999, and 11 July 2010 (Fig. 6), respectively. These values are compatible with a gas temperature \(T_{\text{rot}} = 25\) K, but a closer inspection of the relative intensities of the lines reveals that the night-side temperature \((e > 0\) km s\(^{-1}\)) \(T_{\text{rot}} = 21 ± 5\) K is lower than in the day-side jet: \(T_{\text{rot}} = 31 ± 4\) K. We will use \(T_{\text{rot}} = 30\) K in the sunward jet and \(T_{\text{rot}} = 20\) K elsewhere.

A good fit is obtained with 44% of the outgassing in a narrow jet (opening angle 37° or 0.1 × 4π steradian) with gas velocity of 0.9 km s\(^{-1}\), and the remaining 90% of the sky contain 56% of the outgassing at 0.5 km s\(^{-1}\), as illustrated in Fig. 7. The synthetic line shapes obtained with this modelling provide a reasonable fit to the observed lines (Figs. 2, 4 and 5). We used the same model to analyse the H\(_2\)O 557 GHz line (Fig. 1) and determine the water production rate \(Q_{\text{H}_2\text{O}}\) at the time of the NH\(_3\) observations. However, we assumed \(x_{\text{ne}} = 0.15\) in the excitation model. This value best explains the brightness distribution of the 557 GHz line observed on 19 July (Szutowicz et al. 2011 and in prep.) and is consistent with values found in other comets (Biver et al. 2007; Hartogh et al. 2010). The model reproduces both the line intensity and the Doppler shift of the water line if we set \(Q_{\text{H}_2\text{O}}\) to 2.2 × 10\(^{28}\) mol s\(^{-1}\) (Table 1). This simplistic modelling of the anisotropic outgassing of comet 10P/Tempel 2 will be improved in a future paper (Szutowicz et al., in prep.), but is sufficient to derive accurate production rates and relative abundances. When isotropic outgassing is assumed and the gas temperature set to 25 K, we derive production rates ±15% higher for the short-lived molecules like H\(_2\)S and NH\(_3\), or ±45% higher for other molecules.

### 3.2. Ammonia

The ammonia \(J_K (1_0-0_0)\) line at 572.5 GHz is clearly detected (Fig. 2). The hyperfine structure of the ammonia line is similar to that of the \(J (1-0)\) HCN line: three components \(F (2-1), F (1-1)\) and \(F (0-1)\) with relative intensities 5, 3 and 1, and relative velocities at 0.0, +0.64 and −0.97 km s\(^{-1}\), respectively, with respect to the \(F (2-1)\) frequency of 572.498.371 MHz (Cazzoli et al. 2009). This structure is resolved in the observed spectrum of NH\(_3\) (Fig. 2). The synthetic line profile, based on a model used to fit the optically thin molecular lines observed at IRAM (Figs. 4 and 5, Sect. 3.1), agrees well with the observed profile.

The time variation of the line intensity is marginal (±17%), at a 1.5-σ level of significance. The ammonia production rate was derived with the previously described collision and outgassing pattern model. We assumed a total cross-section of 2 × 10\(^{-14}\) cm\(^2\) for the collisions with neutrals. Collisions with electrons were modelled in the same way as for the other molecules (e.g. Zakharov et al. 2007), i.e. we used the Born approximation for the computation of the cross-sections and set \(x_{\text{ne}} = 0.5\). Infrared pumping through the six strongest \((ν_1, ν_2, ν_3, ν_4, ν_1 + ν_2, \) and \(ν_2 + ν_3)\) vibrational bands was taken into account using the GEISA database (Jacquinet-Husson et al. 2008). Table 2 lists the pumping rates for the main infrared bands of ammonia. The six bands included in our model comprise 95% of the infrared pumping. Our excitation rates agree with those of Kawakita & Mumma (2011). When computing the fluorescence of the vibrational bands down to the fundamental ground state, we did not consider that the \(ν_3 + ν_4\), and \(ν_2 + ν_3\) bands partly deexcite via \(ν_1\). Since these combination bands are weak, this approximation should not affect significantly the rotational populations. The radial evolution of the population of the six lowest ortho levels of NH\(_3\) is shown in Fig. 8.

The NH\(_3\) photodissociation rate is \(β_{\text{th}} = 1.8 × 10^{-4}\) s\(^{-1}\) for the quiet Sun at \(r_0 = 1\) AU (Huebner et al. 1992). Because the NH\(_3\) lifetime is relatively short, radiative processes do not significantly affect the excitation of the rotational levels for comets with high outgassing rates. Indeed NH\(_3\) photodissociates before reaching the rarefied coma where IR pumping and radiative decay dominate over collisional excitation. For moderately active comets like 10P/Tempel 2, these processes are significant: neglecting IR pumping would overestimate the production rate by a factor 2.5 and assuming thermal equilibrium would underestimate it by a factor 1.7. On the other hand, neglecting the anisotropy of the outgassing would increase the production rate by only 14%. The derived ammonia production rate is 1.0 × 10\(^{29}\) mol s\(^{-1}\). The contemporaneous water production

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**Table 2. Ammonia infrared band parameters and excitation rates.**

| Vibrational band | Frequency \([\text{cm}^{-1}]\) | \(A_{\nu}^x\) \([\text{s}^{-1}]\) | \(g_{\nu}^x\) at 1 AU \([\text{s}^{-1}]\) | Used |
|-----------------|-----------------|-----------------|-----------------|-----|
| \(ν_1\)         | 3337            | 7.7             | 3.3 × 10\(^{-5}\) | yes |
| \(ν_2\)         | ≈950            | 16.2            | 27.7 × 10\(^{-5}\) | yes |
| \(2ν_2\)        | ≈1700           | 0.5             | 0.5 × 10\(^{-5}\) | no  |
| \(3ν_2\)        | ≈2600           | 0.1             | 0.05 × 10\(^{-5}\) | no  |
| \(ν_1 + ν_2\)   | 4315            | 1.6             | 0.5 × 10\(^{-5}\) | no  |
| \(ν_3\)         | 3450            | 3.8             | 1.5 × 10\(^{-5}\) | yes |
| \(ν_4\)         | 1630            | 8.7             | 8.5 × 10\(^{-5}\) | yes |
| \(ν_2 + ν_3\)   | 2600            | 0.02            | 0.01 × 10\(^{-5}\) | no  |
| \(ν_3 + ν_4\)   | 5000            | 15              | 3.7 × 10\(^{-5}\) | yes |
| \(ν_1 + ν_4\)   | 4960            | 0.6             | 0.2 × 10\(^{-5}\) | no  |
| \(ν_2 + ν_4\)   | 4450            | 9               | 2.6 × 10\(^{-5}\) | yes |
| \(2ν_4\)        | 3240            | 2.7             | 0.4 × 10\(^{-5}\) | no  |

**Notes.** (a) “Band” (as defined in Crovisier & Encrenaz 1983) Einstein coefficients and total excitation rates (from GEISA database Jacquinet-Husson et al. 2008) computed at 40 K.
being \(\approx 2.2 \times 10^{28} \text{ mol s}^{-1}\) (Table 1), we obtain \([\text{NH}_3]/[\text{H}_2\text{O}] = 0.46 \pm 0.04\%\). This value is very similar to the abundance measured in other comets (Kawakita & Watanabe 2002; Biver et al. 2007; Kawakita & Mumma 2011).

The ortho-to-para ratio (OPR) of ammonia is not directly measured in comets; it is inferred from that of the \(\text{H}_2\) radical and found to be typically 1.1 to 1.2, corresponding to spin temperatures \(\approx 30\) K (Kawakita et al. 2001; Shinnaka et al. 2010, 2011). When analysing our measurement, where only ortho \(\text{NH}_3\) was observed, we assumed OPR = 1 (statistical ratio). Therefore, our determination of the production rate may be overestimated by 5 to 10%.

### 3.3. Molecular abundances from ground based data

Table 1 provides production rates inferred for \(\text{H}_2\text{O}\) and \(\text{CH}_3\text{OH}\) in 1999, and for \(\text{H}_2\text{O}, \text{CH}_3\text{OH}, \text{CS}, \text{H}_2\text{S}\) and \(\text{CH}_3\text{CN}\) in 2010. Based on contemporaneous water production of \(\approx 1.8 \times 10^{28} \text{ mol s}^{-1}\) (Szutowicz et al., in prep.) at the time of IRAM observations in 2010 (i.e. \(\approx 9\) days earlier than the \(\text{NH}_3\) observation), the derived molecular abundances are given in Table 3. These abundances are typical of short-period comets, with \(\text{CH}_3\text{OH}\) and \(\text{H}_2\text{S}\) abundances in the middle-low part of the observed range (Crovisier et al. 2009a,b). The average cometary [CS]/[HCN] ratio is close to 0.8, with a \(\rho = 0.8\) dependence (Biver et al. 2006, 2011). The observed value in Tempel 2 is on the high side given that we would expect a value around 0.6 at \(r_h = 1.42\) AU. Ammonia is the dominant source of nitrogen in the icy cometary ices (\(\approx 80\%\)). Other possible sources of nitrogen in comets are HNC, and \(\text{HC}_3\text{N}\), which were always below the HCN abundance in all comets in which they were detected or searched for (e.g., Bockelé-Morvan et al. 2004). Note that even though \(\text{HC}_3\text{N}\) was not searched in depth in comet 10P, low-resolution spectra on 11.3 July provide an upper limit on the \(\text{H}_2\text{CN} J (16−15)\) line, which yields in any case \([\text{HC}_3\text{N}] < 0.3 \times [\text{NH}_3]\).

In 1999 the comet had a higher activity on 12 September when \(\text{CH}_3\text{OH}\) was observed and HCN reached a maximum. At other dates, however, it was at least 50\% less active than in 2010. This is likely due to a larger perihelion distance (1.48 vs. 1.20 AU). Meanwhile, the \([\text{CH}_3\text{OH}]/[\text{HCN}]\) ratio did not change in 11 years after two orbits around the Sun and the prominent jet feature was still there: the line asymmetry is still present and visible images showed a similar northwards jet structure (Biver, priv. comm.) at both apparitions.

### 4. Conclusion

Ammonia was directly observed in comet 10P/Tempel 2 through its fundamental rotational line. The hyperfine structure of the line is resolved for the first time in an astronomical object, thanks to the narrow width of the cometary line. The abundance of ammonia is found to be \(0.46 \pm 0.04\%\) relative to water. This is similar to values measured in other comets, making ammonia the major source of nitrogen in icy cometary ices. The abundances of HCN, \(\text{CH}_3\text{OH}, \text{CS}, \text{H}_2\text{S}\) are typical of short-period comets, though on the mid-low range. The comet displayed strongly blueshifted lines indicative of a strong asymmetry in the outgassing. This asymmetry is present for all species, which also suggests a common source for all and compositional homogeneity. Based on simple modelling, about half of the outgassing is in a narrow sunward jet with a higher outgassing speed (0.9 km s\(^{-1}\)) than outside the jet (0.5 km s\(^{-1}\)).

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