Volatile composition of comet C/2004 Q2 (Machholz)

M. de Val-Borro[1,2], P. Hartogh[1], C. Jarchow[1], M. Rengel[1], G. L. Villanueva[3], M. Küppers[4], N. Biver[5], D. Bockelée-Morvan[5], J. Crovisier[5]

[1]Max Planck Institute for Solar System Research, [2]Princeton University, [3]NASA Goddard Space Flight Center, [4]European Space Astronomy Center, [5]LESIA, Observatoire de Paris

deval@mps.mpg.de

Abstract

We have obtained production rates of several volatiles (CH_3OH, HCN, $H^{13}CN$, HNC, H_2CO, CO and CS) in comet C/2004 Q2 (Machholz) using the Submillimeter Telescope at the Arizona Radio Observatory. We calculated the synthetic profiles using a radiative transfer code that includes collisions between neutrals and electrons, and the effects of radiative pumping of the fundamental vibrational levels by solar infrared radiation. Furthermore, multiline observations of the CH_3OH J (7–6) series allows us to estimate the rotational temperature using the rotation diagram technique. We find that the CH_3OH population distribution of the levels sampled by these lines can be described by a rotational temperature of 40 ± 3 K. Derived mixing ratios relative to hydrogen cyanide are $CO/CH_3OH/H_2CO/CS/HNC/H^{13}CN/HCN = 30.9/24.6/4.8/0.57/0.031/0.013/1$ assuming a pointing offset of 8″ due to the uncertain ephemeris at the time of the observations and the telescope pointing error. The measured relative molecular abundances in C/2004 Q2 (Machholz) are between low to typical values of those obtained in Oort Cloud comets suggesting that it has visited the inner Solar System previously and undergone thermal processing. From a tentative $H^{13}CN$ detection, the measured value of 97 ± 30 for the $H^{12}CN/H^{13}CN$ isotopologue pair is consistent with a telluric value. The outgassing variability observed in the HCN production rates over a period of 2 hours is consistent with the rotation of the nucleus derived using different observational techniques.

1. Introduction

Comets spend most of their lifetime in the outer Solar System and therefore have not undergone considerable thermal processing. Line emission from cometary atmospheres at submillimeter and radio wavelengths is a very useful tool to study their physical and chemical conditions and relation with other bodies in the Solar System (Biver et al. 2002; Bockelée-Morvan et al. 2004). The coma structure and expansion velocity can be derived by fitting the observed line shapes using a molecular excitation code. In addition, mixing ratios of volatiles such as CH_3OH, CO and CS can be compared with observed chemical abundances in protoplanetary disks to improve our understanding of planet formation processes.

We present high-resolution spectroscopic observations of several volatiles from comet C/2004 Q2 (Machholz) acquired at the Submillimeter Telescope (SMT). Seven species are detected, namely CH_3OH, HCN, HNC, H_2CO, CO, CS and a marginal detection of $H^{13}CN$. The comet was observed shortly pre-perihelion in January 2005 when it was at a distance ~ 0.36 AU from Earth. These observations provide information about the outgassing of several molecules and an isotopologue of HCN relative to HCN, which is often used as a proxy for water in cometary taxonomies. We calculate the CH_3OH rotational temperature of the ground vibrational level from several rotational lines and production rates for the observed molecules using a radiative transfer code to fit the observed line intensities.

2. Results

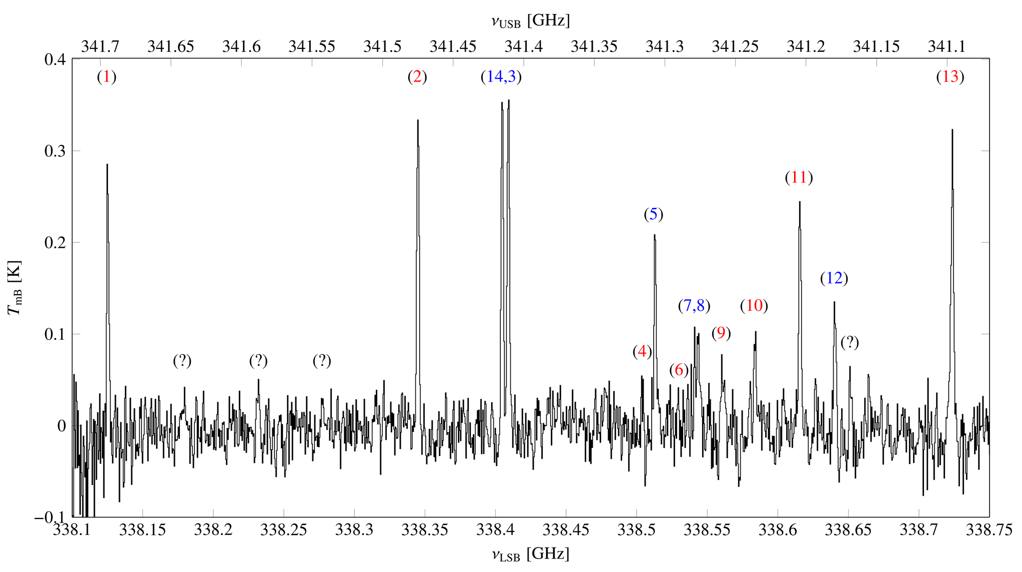

Figure 1: *CH_3OH averaged spectrum obtained on 13.95 UT January 2005. The lower and upper x-axis scales represent the frequency of the lower and upper sidebands, respectively. There is a blend of three A^+ and A^- emission lines at 338.513 GHz (label 5). The observed line at 338.722 GHz is a blend of two E components (label 13). The A^- line at 341.416 GHz (label 14) is in the upper sideband close to the A^+ transition at 338.409 GHz (label 3). A marginal detection of the E line at 338.530 GHz is indicated by label 6.*

A spectral line survey of primary volatile species in comet C/2004 Q2 (Machholz) was made using the SMT telescope located at the Mount Graham International Observatory. The SMT has a parabolic 10-m primary dish and a hyperbolic secondary reflector. The observations were performed with the 0.8 mm double sideband receiver using various spectrometers (de Val-Borro et al. 2011). One of the purposes of the observations was to test the performance of the newly installed high-resolution CTS built at the Max Planck Institute for Solar System Research (Villanueva & Hartogh 2004).

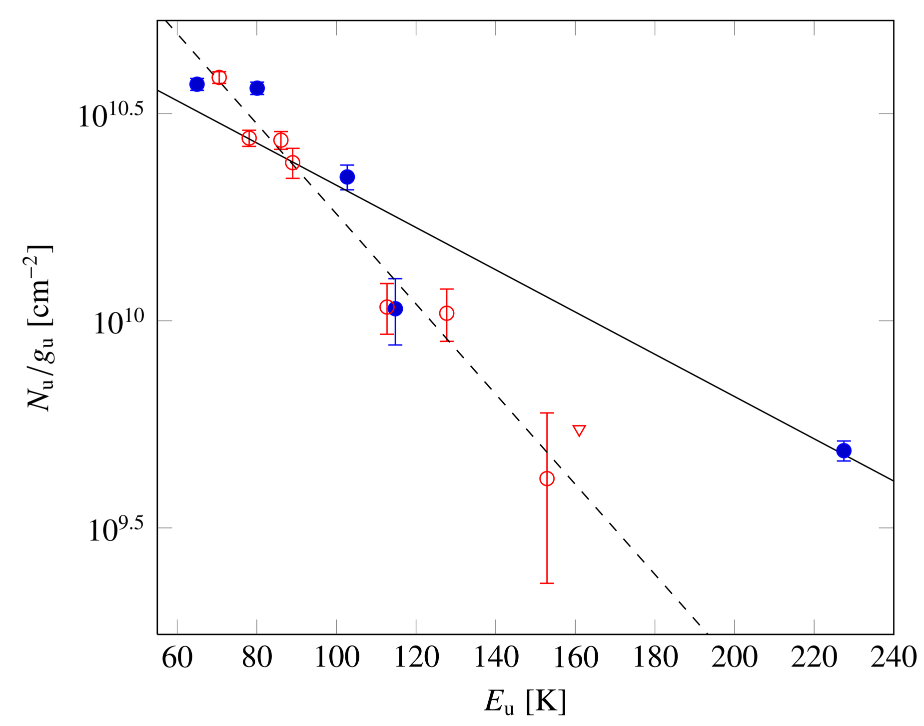

Figure 2: *Rotation diagram for CH_3OH lines in comet C/2004 Q2 (Machholz) including 1-σ uncertainties. The column density of the upper level divided by its degeneracy in logarithmic scale is plotted against the energy of the upper level. Blue circles are A^+ and A^--CH_3OH lines, Red circles denote E-CH_3OH transitions and the triangle indicates the 3-σ upper limit on the 7_4–6_4E transition at 338.530 GHz. The solid line shows the best linear fit with a derived rotational temperature of 85 ± 7 K. The dashed line shows the best linear fit excluding the 13_1–13_0A^- transition at 342.730 GHz with a derived rotational temperature of 40 ± 3 K.*

We adopt a molecular excitation and radiative transfer model based on the publicly available Accelerated Monte Carlo radiative transfer code *ratran* is used to calculate the populations of the rotational levels as function of the distance from the nucleus for various molecules and line emission in the cometary coma. We used the one-dimensional spherically symmetric version of the code that has been used to interpret *Herschel* cometary observations (see e.g. Hartogh et al. 2010).

Table 1: *Production rates of detected species relative to HCN and H_2O in comet C/2004 Q2 (Machholz) with statistical uncertainties.*

Molecule	Q (molec. s^{-1})	Q/Q_{HCN}	Q/Q_{H_2O} (%)
HCN	$(2.26 \pm 0.02) \times 10^{26}$	1	0.084 ± 0.001
CO	$(7.0 \pm 0.6) \times 10^{27}$	30.9 ± 2.6	2.6 ± 0.2
CH_3OH	$(5.5 \pm 0.6) \times 10^{27}$	24.6 ± 2.5	2.0 ± 0.2
H_2CO	$(3.87 \pm 0.20) \times 10^{26}$	1.7 ± 0.1	0.14 ± 0.01
	$(1.09 \pm 0.06) \times 10^{27}$	4.8 ± 0.3	0.40 ± 0.02
CS	$(1.15 \pm 0.04) \times 10^{26}$	$(5.1 \pm 1.7) \times 10^{-1}$	$(4.3 \pm 0.1) \times 10^{-2}$
	$(1.29 \pm 0.04) \times 10^{26}$	$(5.7 \pm 1.9) \times 10^{-1}$	$(4.8 \pm 0.2) \times 10^{-2}$
HNC	$(7 \pm 2) \times 10^{24}$	$(3.1 \pm 0.9) \times 10^{-2}$	$(2.6 \pm 0.7) \times 10^{-3}$
$H^{13}CN$	$(3 \pm 1) \times 10^{24}$	$(1.3 \pm 0.5) \times 10^{-2}$	$(1.1 \pm 0.4) \times 10^{-3}$

Retrieved molecular abundances relative to water are comparable to those obtained in Oort Cloud comets. Our Q_{HCN}/Q_{H_2O} mixing ratio of $\sim 0.084\%$ is slightly lower than the typical value of 0.1% observed at radio wavelengths, and 50% lower than those found by Bonev et al. (2009) from averaged 28 November 2004 and 19 January 2005 observations and by (Kobayashi & Kawakita 2009) from observations on 30 January 2005 using the same instrument. The observed difference between our radio measurements and those derived at infrared wavelengths is somewhat typical. The origin of this systematic difference is still unknown, and could be related to the assumed excitation process and the source of HCN in comets. The mixing ratio of CH_3OH relative to H_2O agrees with the infrared measurement in comet C/2004 Q2 (Machholz) by Bonev et al. (2009) performed on 19 January 2005 at $r_h = 1.208$ AU that is closer in time with our observations. The averaged CO production rate measured on 13 and 16 January agrees with that obtained by Bonev et al. (2009) on 29 November 2004 at $r_h = 1.493$ AU ($(6.3 \pm 0.3) \times 10^{27}$molec. s^{-1}) within confidence limits. In contrast the Q_{CO}/Q_{H_2O} mixing ratio of $\sim 2.6\%$ is almost a factor of two smaller that derived by Bonev et al. (2009). For a parent molecule distribution, the derived Q_{H_2CO}/Q_{H_2O} ratio is 0.14%, and Q_{H_2CO}/Q_{HCN} is 1.7%, which is more reliable since these molecules were observed simultaneously. These values are intermediate between those measured by Bonev et al. (2009) and (Kobayashi & Kawakita 2009).

References

Biver, N., Bockelée-Morvan, D., Crovisier, J., et al. 2002, Earth Moon and Planets, 90, 323

Bockelée-Morvan, D., Crovisier, J., Mumma, M. J., & Weaver, H. A. 2004, in Comets II, ed. M. C. Festou, H. U. Keller, & H. A. Weaver (Univ. Arizona Press), 391–423

Bonev, B. P., Mumma, M. J., Gibb, E. L., et al. 2009, ApJ, 699, 1563

de Val-Borro, M., Jarchow, C., Hartogh, P., Villanueva, G., & Küppers, M. 2011, Advances in Geosciences, 25, 149

Hartogh, P., Crovisier, J., de Val-Borro, M., et al. 2010, A&A, 518, L150

Kobayashi, H. & Kawakita, H. 2009, ApJ, 703, 121

Villanueva, G. & Hartogh, P. 2004, Experimental Astronomy, 18, 77