CHEMICAL COMPOSITION DIVERSITY AMONG 24 COMETS OBSERVED AT RADIO WAVELENGTHS

Nicolas Biver (`nicolas.biver@obspm.fr`)
ESA/ESTEC, Sci-Sb, Keplerlaan 1, 2200-AG Noordwijk, The Netherlands

Dominique Bockelée–Morvan, Jacques Crovisier, Pierre Colom and Florence Henry
LESIA, Observatoire de Paris-Meudon, 5 pl. J.Janssen, F-92195 Meudon, France

Raphaël Moreno
Institut de Radio Astronomie Millimétrique (IRAM), 300, rue de la Piscine, F-38406 Saint Martin d'Hères, France

Gabriel Paubert
IRAM, Avd. Divina Pastora, 7, 18012 Granada, Spain

Didier Despois
Observatoire de Bordeaux, BP 89, F-33270 Floirac, France

Dariusz C. Lis
Caltech, MS 320-47, Pasadena, CA 91125, U.S.A

Abstract. We present a comparative study on molecular abundances in comets based on millimetre/submillimetre observations made with the IRAM 30-m, JCMT, CSO and SEST telescopes. This study concerns a sample of 24 comets (6 Jupiter-family, 3 Halley-family, 15 long-period) observed from 1986 to 2001 and 8 molecular species (HCN, HNC, CH_3CN, CH_3OH, H_2CO, CO, CS, H_2S). HCN was detected in all comets, while at least 2 molecules were detected in 19 comets.

From the sub-sample of comets for which contemporary H_2O production rates are available, we infer that the HCN abundance relative to water varies from 0.08% to 0.25%. With respect to other species, HCN is the molecule which exhibits the lowest abundance variation from comet to comet. Therefore, production rates relative to that of HCN can be used for a comparative study of molecular abundances in the 19 comets. It is found that: CH_3OH/HCN varies from ≤ 9 to 64; CO/HCN varies from ≤ 24 to 180; H_2CO/HCN varies between 1.6 and 10; and H_2S/HCN varies between 1.5 and 7.6.

This study does not show any clear correlation between the relative abundances and the dynamical origins of the comets, or their dust-to-gas ratios.

Keywords: Comets, Radio observations, Molecules

1. Introduction

The last decade has proven the efficiency of microwave observations in investigating the chemical composition of cometary atmospheres. The composition of cometary nuclei is of strong interest for understanding their origin. As these objects should not have evolved so much since their formation, their composition provides clues to the composition in the outer regions of the solar nebula where they formed. The ultimate goal of this chemical composition survey of comets is to find out eventually comet families according to their chemical content and link them to their origin (e.g. Jupiter-family comets or Oort-Cloud comets) and likely formation region (giant planets region to Kuiper Belt). This paper provides a first synthesis of a 15-year investigation at radio wavelengths.

Up to now, chemical diversity among comets has been investigated from narrowband photometry of radicals in the visible (A'Hearn et al., 1995). A class of *carbon-depleted* comets, tentatively associated with Jupiter-family comets, was noted. One of the goals of the present study is to investigate whether such a diversity can be confirmed by the direct observation of the sublimation products of nucleus ices.

2. Observations

The radio lines of 8 molecules (HCN, HNC, CH_3CN, CH_3OH, H_2CO, CO, CS, H_2S) were searched for with the Institut de Radio Astronomie Millimétrique (IRAM) 30-m or 4×–5×15-m Plateau-de-Bure interferometer, the James Clerk Maxwell Telescope (JCMT) 15-m, the Caltech Submillimeter Observatory (CSO) 10.4-m or the Swedish-ESO Submillimetre Telescope (SEST) 15-m radio telescopes. A list of the 24 comets detected in at least one line, with particularities and references, is given in Table I[1]. From a statistical point of view, at least 5 of these molecules were searched for in 11 of the comets and at least two molecules were detected in 19 comets out of the 24.

3. Data reduction and production rates

In most cases the production rates were derived following the methodology and parameters described in Biver et al. (1999). To model the gas density in the coma, an isotropic steady-state outflow described by a Haser density radial profile was assumed, unless stated otherwise in the references given in Table I. The line shapes have been used to

---

[1] We have excluded from this study comets C/1997 J2 (Meunier-Dupouy), observed at 3 AU in which only CO and CH_3OH were detected, and 29P/Schwassmann-Wachmann 1, observed at 6 AU in which only CO was detected. The upper limits obtained on HCN production rates in both comets do not provide any significant constraint

Table I. Observed comets and references

Comet	N[1]	origin[2]	particularities	references[3]
2P/Encke	–	JF		
10P/Tempel 2	20	JF	strong jet	
19P/Borrelly	19	JF	strong jet	[1]
21P/Giacobini-Zinner	21	JF	no or low CO	
22P/Kopff	22	JF	low CO	[2]
45P/Honda-M.-P.	–	JF		[2]
1P/Halley	–	HF		[3]
23P/Brorsen-Metcalf	–	HF		[2, 4]
109P/Swift-Tuttle	25	HF	strong jet	[2, 5]
			HCN, CH_3OH rich	[6]
C/1989 X1 (Austin)	1	LPC, DN	CH_3OH rich	[2, 4, 7, 8]
C/1990 K1 (Levy)	2	LPC		[2, 4, 7, 8]
C/1995 O1 (Hale-Bopp)	3	LPC, old	HCN, H_2CO, H_2S, CO, CS rich	[9, 10]
C/1996 B1 (Szczepanski)	4	LPC, old	CH_3OH rich	[2]
C/1996 B2 (Hyakutake)	5	LPC	CO rich	[11]
C/1996 Q1 (Tabur)	6	LPC, old	CH_3OH poor disintegrated	[2]
C/1998 M5 (LINEAR)	–	LPC		
C/1998 P1 (Williams)	–	LPC	CO rich	
C/1998 T1 (LINEAR)	10	LPC		
C/1998 U5 (LINEAR)	–	LPC, old		
C/1999 H1 (Lee)	12	LPC	CH_3OH rich	[12]
C/1999 S4 (LINEAR)	13	LPC, DN	CH_3OH, CO poor disintegrated	[13]
C/1999 T1 (McNaught-H.)	14	LPC	CO rich	[14]
C/2000 WM_1 (LINEAR)	15	LPC	CO, H_2S poor	
C/2001 A2 (LINEAR)	16	LPC	CO poor, H_2S rich	[14]

[1] Reference number in Figs 2–4;
[2] JF: Jupiter family; HF: Halley family; LPC long-period comet; DN: dynamically new (semi-major axis $a > 10\,000$ AU); old: orbital period $< 10\,000$ years;
[3] [1]: Bockelée-Morvan et al. (2002a); [2]: Biver (1997); [3]: Despois et al. (1986); [4]: Colom et al. (1992); [5]: Bockelée-Morvan et al. (1994b); [6]: Despois et al. (1996); [7]: Bockelée-Morvan et al. (1994); [8]: Crovisier et al. (1991); [9]: Biver et al. (2002); [10]: Bockelée-Morvan et al. (2000); [11]: Biver et al. (1999); [12]: Biver et al. (2000); [13]: Bockelée-Morvan et al. (2001); [14]: Crovisier et al. (2001).

derive an estimate of the gas outflow velocity (v_{exp}). When available, rotational temperatures of methanol or other species were used to derive the gas temperature. Otherwise, the gas temperature was assumed on the basis of observations in comets of similar activity at similar heliocentric distances. Water outgassing rates were taken from the current literature, namely Crovisier et al. (2002a, 2002b), when available, or extrapolated on the basis of the magnitude–water production rates correlation formula $\log Q_{\mathrm{H_2O}} = 30.74 - 0.24(m_1 - 5 \log \Delta)$, from Jorda et al. (1992).

4. Comparison of chemical abundances

Most relative abundances were derived from the ratio of production rates to water outgassing rates. HCN was also used as a reference as it is the easiest molecule to detect close to the Sun and was detected in the 24 comets observed within 1.5 AU from the Sun. Since HCN was often observed quasi simultaneously and with a similar beam size as the other molecules studied here, the abundances relative to HCN are more reliable. They have been used in Figs 3–4.

The sample (Table I) comprises 4 Jupiter-family comets, 2 Halley-family comets and 13 long-period comets (2 dynamically new, 3 “old” with period of less than 10 000 years), in which HCN plus at least one other molecule were detected. Fig. 1 shows the current status of the histogram analysis of the abundances relative to water (HNC/HCN for HNC) in those comets, in which some of the 8 molecular species abundances could be measured. Table II summarizes the abundance ranges observed.

No significant difference could be found between the different comet classes, but it must be emphasized that our analysis is still preliminary, and that the sizes of the sub-samples are limited. We also investigated the possibility of a correlation between relative molecular abundances with the dust-to-gas ratio of the comets, traced by the $Af\rho/Q[\mathrm{CN}]$ ratio deduced from visible spectrophotometry. No trend could be found.

5. Results

5.1. CN-BEARING MOLECULES

HCN was the first molecule firmly detected at millimetre wavelengths in a comet, in 1P/Halley in 1985. It has subsequently been detected in 23 comets. Its measured abundance relative to water ranges between

Table II. Molecular abundances in 24 comets

Molecule	comets observed		Q/Q_{water}		Q/Q_{HCN}	
	detected	upper limit	mini	maxi	mini	maxi
HCN	24	0	0.08 %	0.25 %	1	1
HNC	5	2	< 0.003%	0.035%	< 0.03	0.17
CH_3CN	4	0	0.013%	0.035%	0.08	0.23
CH_3OH	15	2	< 0.9 %	6.2 %	< 9	64
CO	5	4	< 1.7 %	23 %	< 19	180
H_2CO	13	2	0.13 %	1.3 %	1.6	10
H_2S	11	3	0.12 %	1.5 %	1.5	7.6
CS	9	0	0.05 %	0.17 %	0.5	1.2

0.08% and 0.25% – when a water outgassing rate is available – and is one of the least variable from comet to comet (Figs 1–2). For this reason, HCN is also often taken as a reference.

CH_3CN has been detected in only 4 comets (including one marginal detection) since 1996, with an abundance relative to HCN between 0.08 and 0.23.

HNC has been detected in 5 comets since 1996, but its origin is puzzling. While production through chemical reaction in the coma of Hale-Bopp was invoked to explain its increasing abundance closer to the Sun, it cannot explain abundances relative to HCN in the range 6–17% observed in other comets. It also seems that there is a general trend of increasing HNC/HCN ratio for decreasing r_h in all comets.

5.2. CO-BEARING MOLECULES

Methanol (CH_3OH) has been detected in 17 comets since C/1989 X1 (Austin) in 1990. Several lines have often been simultaneously detected, enabling temperature measurements. Its abundance relative to water (Table II, Figs 1–2) varies at least twice as much as for HCN: $< 0.9\%$ to 6.2%, with most comets (including all Jupiter-family comets) being in the 1.5–2.8% range.

Formaldehyde (H_2CO): this molecule has been detected in 13 comets since 1989. We have assumed a distributed source with a Haser equivalent density distribution and a parent lifetime of about 10 000 s at $r_h = 1$ AU, as suggested by many observations (Colom et al., 1992; Biver et al., 1999; 2002) – this is equivalent to a parent scale-length of 8000 $r_h^{1.5}$ for an average expansion velocity of 0.8 $r_h^{-0.5}$ km s^{-1} (Biver et al., 1999; 2000). Its abundance relative to water varies by one order of

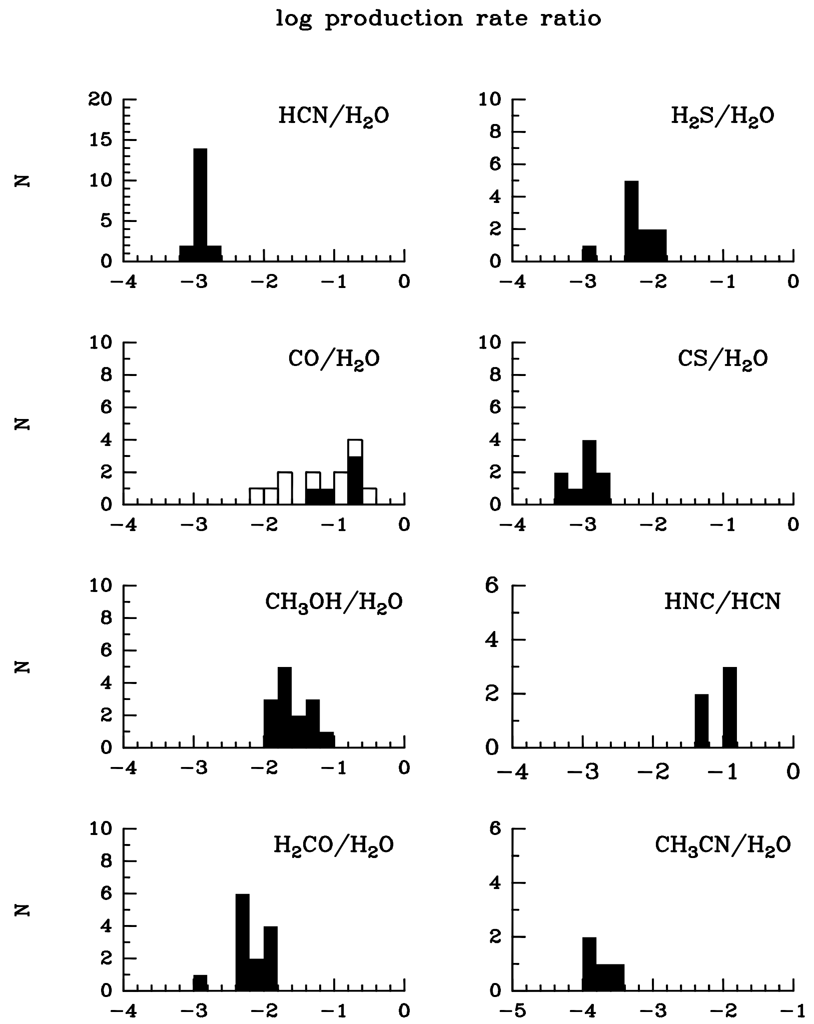

Figure 1. Histogram analysis of the abundances relative to water (excepted for HNC, for which the HNC/HCN abundance ratio is of higher significance) of all eight molecules studied here. In the case of CO, unfilled bars are additional information provided by the more extensive study carried out in the infrared (DiSanti et al. (2000) and previous observations) or UV (Feldman et al. 1997). See also Huebner (2002) and Bockelée-Morvan and Crovisier (2002b) for more extensive studies of the chemical content of comets.

magnitude and a factor of 6 relative to HCN. Curiously, the comets that are abundant in formaldehyde are also abundant in methanol (Fig. 3), but owing to the long lifetime of CH_3OH (about 77 000 s at 1 AU), it is not a likely parent molecule for H_2CO. Large polymers thermally degraded on grains are a more likely parent source for formaldehyde, as suggested by Cottin et al. (2001).

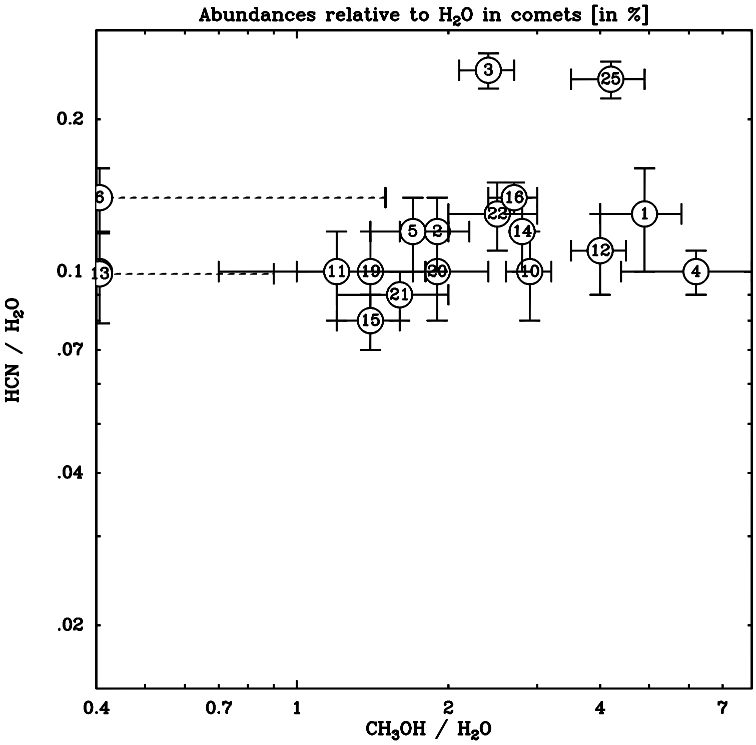

Figure 2. HCN abundance versus CH_3OH abundance (relative to water) in comets. The numbers inside the circles refer to comets as listed in Table I. Dotted line error bars with comet number on one of the axis are 3-σ upper limits for non-detections.

CO: other techniques (infrared and UV) are usually more sensitive to measure the CO abundance in comets close to the Sun. But this molecule can have a high abundance (CO/HCN > 85 in 4 long-period comets) above $\approx 10\%$ relative to water close to the Sun and much higher further away. Far from the Sun, CO is the main driver of cometary activity and can be detected in the radio out to more than 14 AU (Biver et al., 2002; Biver, 2001). In 4 other comets (including short-period comets) we found CO/HCN below 40. Hence CO might not be the second most abundant species in these comets.

5.3. SULPHUR-BEARING MOLECULES

Hydrogen sulphide (H_2S) was first detected in comets in 1990 (Crovisier et al., 1991) and has been detected in 11 comets since. Its abundance relative to HCN varies by a factor 5 – and even by one order of magnitude with respect to water – but most comets have a ratio

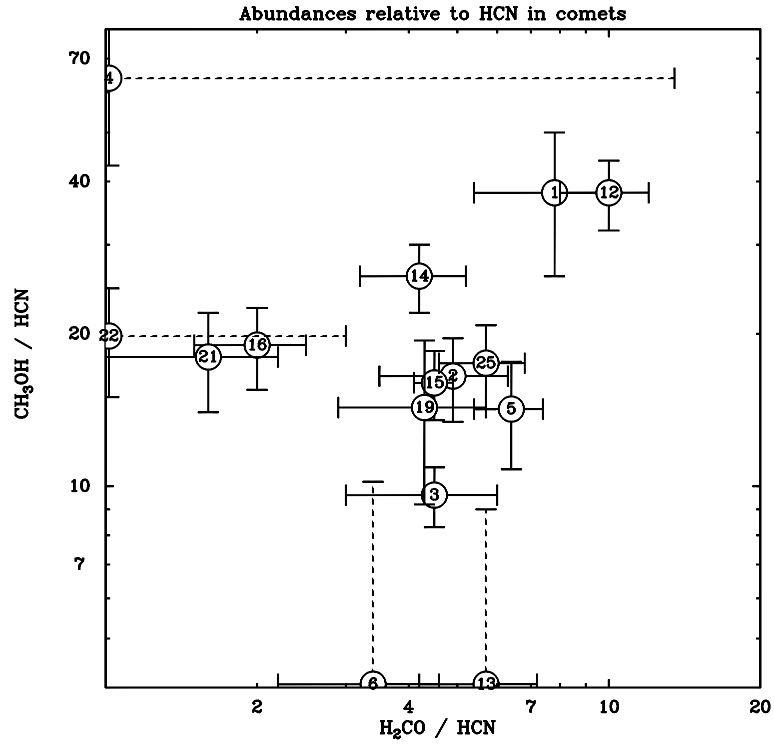

Figure 3. CH_3OH abundance versus H_2CO abundance (relative to HCN) in comets. The comets that are rich in methanol seem also to be abundant in formaldehyde.

H_2S/HCN between 4 and 6 (Fig. 4). Variations in H_2S abundances seem completely uncorrelated with dynamical origin.

CS has been recently observed in the radio but was observed in comets in the UV well before 1996. So far we have assumed (in the 9 comets in which we detected CS) that it is the photo-dissociation product of CS_2 (Biver et al., 1999). However, it was found that the CS/HCN ratio increased with heliocentric distance as $r_h^{-0.7}$ (Biver et al., 1999; 2002). This trend is observed in some other comets and was previously observed in comet 1P/Halley by Meier and A'Hearn (1997). This is puzzling as CS_2 is a very volatile molecule and is not expected to sublimate less easily than H_2O or HCN further away from the Sun. Taking out this trend with r_h, the CS/HCN ratio is close to 0.8 at $r_h \approx 1$ AU in most comets.

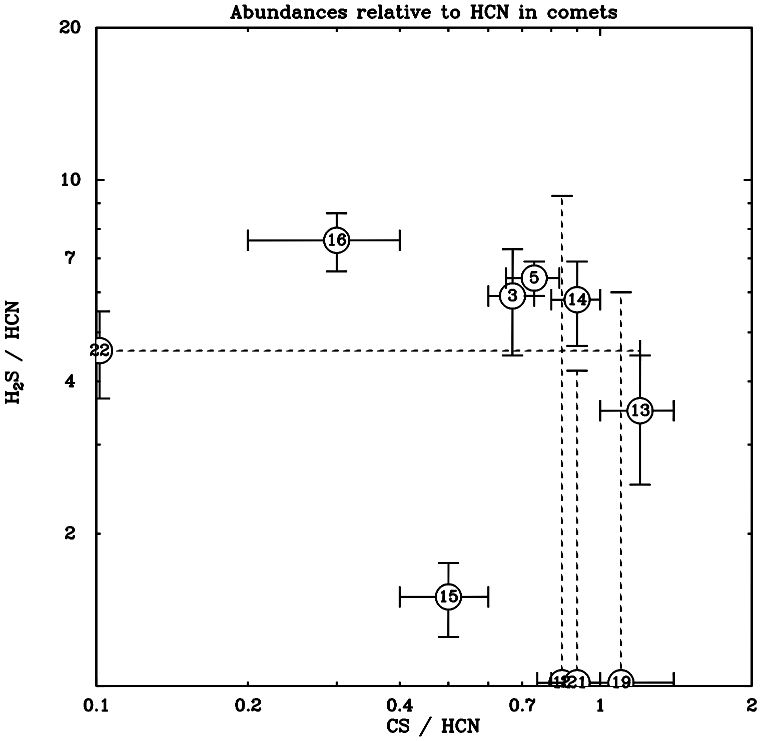

Figure 4. H_2S abundance versus CS abundance (relative to HCN) in comets.

6. Conclusion

This work is still in an early phase: a larger sample of comets and a multi-dimensional analysis of the grouping of the comets according to their chemical composition are obviously needed. Heliocentric trends (for HNC, CS and formaldehyde) should be further understood before any definitive conclusions can be drawn. They possibly indicate that the chemical composition of cometary comae is probably not fully representative of nuclei composition. In the current state, comparison for similar heliocentric distances only reveals that Jupiter-family comets, likely formed in the Kuiper Belt, do not show distinct compositions from the others, presumably coming from the Oort Cloud. But one might also expect a larger scatter among long-period comets if they were formed over a wider range of heliocentric distances (Jupiter to Neptune region) in the proto-planetary nebula.

Acknowledgements

We are grateful to the IRAM, JCMT, CSO and SEST staff and other observers for their assistance during the observations. IRAM is an international institute cofunded by the CNRS, the Max Planck Gesellschaft and the Instituto Geografico Nacional, Spain. The JCMT is operated in behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada. The CSO is is supported by National Science Foundation grant AST 99-80846. The SEST is operated jointly by the Swedish National Facility for Radio Astronomy, and by the European Southern Observatory.

References

A'Hearn, M.F., Millis, R.L., Schleicher, D.G., Osip, D.J. and Birch, P.V.: 1995, "The ensemble properties of comets: results from narrowband photometry of 85 comets, 1976-1992" *Icarus*, **118**, 223–270

Biver, N: 1997, "Molécules Mères Cométaires: Observations et Modélisations" *PhD thesis, Paris-7 University*

Biver, N., Bockelée-Morvan, D., Colom, P., et al.: 1999 "Long-Term Evolution of The Outgassing Of Comet Hale-Bopp From Radio Observations", *Earth, Moon, and Planets*, **78**, 5–11

Biver, N., Bockelée-Morvan, D., Crovisier, J., et al.: 1999, "Spectroscopic Monitoring of Comet C/1996 B2 (Hyakutake) with the JCMT and IRAM Radio Telescopes", *Astron. J.*, **118**, 1850–1872

Biver, N., Bockelée-Morvan, D., Crovisier, J., et al.: 2000, "Spectroscopic Observations of Comet C/1999 H1 (Lee) with the SEST, JCMT, CSO, IRAM, and Nançay Radio Telescopes", *Astron. J.*, **120**, 1554–1570

Biver, N.: 2001 "Correlation Between Visual Magnitudes and Outgassing Rate of CO in Comets Beyond 3 AU" *International Comet Quarterly*, **23-3**, 85–93

Biver, N., Bockelée-Morvan, D., Colom, P., et al.: 2002, "The 1995-2001 Long Term Monitoring of Comet C/1995 O1 (Hale-Bopp) at Radio Wavelengths" *Earth, Moon, and Planets, these proceedings*

Bockelée-Morvan, D., Crovisier, J., Colom, P. and Despois, D.: 1994, "The rotational lines of methanol in comets Austin 1990 V and Levy 1990 XX", *Astron. Astrophys.*, **287**, 647–665

Bockelee-Morvan, D., Padman, R., Davies, J. K. and Crovisier, J.: 1994, "Observations of submillimetre lines of CH_3OH, HCN, and H_2CO in Comet P/Swift-Tuttle with the James Clerk Maxwell Telescope" *Planetary and Space Science*, **42**, 193–198

Bockelée-Morvan, D., Lis, D.C., Wink, J.E. et al.: 2000, "New molecules found in comet C/1995 O1 (Hale-Bopp). Investigating the link between cometary and interstellar material" *Astron. Astrophys.*, **353**, 1101–1114

Bockelée-Morvan D., Biver, N., Moreno, R. et al.: 2001, "Outgassing Behavior and Composition of Comet C/1999 S4 (LINEAR) During Its Disruption" *Science*, **292**, 1339–1343

Bockelée-Morvan, D., Biver, N., Colom, P., Crovisier, J., Festou, M.C., Henry, F., Lecacheux, A. and Weaver H.A.: 2002a, "Radio Investigation of 19P/Borrelly in support to Deep Space 1 flyby" *Earth, Moon, and Planets*, *these proceedings*

Bockelée-Morvan, D. and Crovisier, J.: 2002b, "The Lesson of Comet Hale-Bopp for Coma Chemistry: Observations and Theory" *Earth, Moon, and Planets*, *these proceedings*

Colom, P., Crovisier, J., Bockelée-Morvan, D., Despois, D. and Paubert, G.: 1992, "Formaldehyde in comets I. Microwave observations of P/Brorsen-Metcalf (1989 X), Austin (1990 V) and Levy (1990 XX)", *Astron. Astrophys.*, **264**, 270–281

Cottin, H., Gazeau, M. C., Benilan, Y. and Raulin, F.: 2001, "Polyoxymethylene as Parent Molecule for the Formaldehyde Extended Source in Comet Halley", *Astrophys. J.*, **556**, 417–420

Crovisier, J., Bockelée-Morvan, D., Colom, P., Despois, D. and Paubert, G.: 1991, "Microwave observations of hydrogen sulfide and searches for other sulfur compounds in Comets Austin (1989c1) and Levy (1990c)" *Icarus*, **93**, 246–258

Crovisier, J., Biver, N., Moreno, R. et al.: 2001 "Spectroscopic Investigation of Comets C/1999 T1 (McNaught-Hartley) and C/2001 A2 (LINEAR) at Radio Wavelengths: Evidence for Chemical Diversity" *B.A.A.S*, **33**, 1121

Crovisier, J., Gérard, E., Colom, P. and Bockelée-Morvan, D.: 2002a, "Observation of the OH Radio Lines of Comets at Nançay – Recent Developments" *Earth, Moon, and Planets*, *these proceedings*

Crovisier, J. ,Colom, P., Gérard, E., Bockelée-Morvan, D., and Bourgois, G.: 2002b, "Observations of the OH 18-cm lines in comets at Nançay: The data base. Observations made from 1982 to 1999" *Astron. Astrophys.*, in press

Despois, D., Crovisier, J., Bockelée-Morvan, D., Gérard, E. and Schraml, J.: 1986 "Observations of hydrogen cyanide in comet Halley" *Astron. Astrophys.*, **160**, L11–L12

Despois, D., Biver, N., Bockelée-Morvan, D., Colom, P., Crovisier, J., Paubert, G.: 1996 "Radio line observations of comet 109P/Swift-Tuttle at IRAM" *Planetary and Space Science*, **44**, 529–539

DiSanti, M. A., Mumma, M. J., Dello Russo, N., Magee-Sauer, K., Novak, R. and Rettig, T. W.: 2000, "A Comparison of CO Abundances from Infrared Observations of Recent Comets" *B.A.A.S.*, **32**, 1071

Feldman, P.D., Festou, M.C., Tozzi, G.P. and Weaver, H.A.: 1997, "The CO_2/CO Abundance Ratio in 1P/Halley and Several Other Comets Observed by IUE and HST" *Astrophys. J.*, **475**, 829–834

Huebner, W.F.: 2002, "Chemical Composition of Comets: Observations and Models" *Earth, Moon, and Planets*, *these proceedings*

Jorda, L., Crovisier, J. and Green, D. W. E.: 1992, "The correlation between water production rates and visual magnitudes in comets" *In Lunar and Planetary Inst.*, Asteroids, Comets, Meteors 1991, 285–288

Meier, R., Eberhardt, P., Krankowsky, D. and Hodges, R.R.: 1993, "The extended formaldehyde source in comet Halley", *Astron. Astrophys.*, **277**, 677–690

Meier, R. and A'Hearn, M.F.: 1997 "Atomic Sulfur in Cometary Comae Based on UV Spectra of the S I Triplet near 1814 Å" *Icarus*, **125**, 164–194

Rodgers, S.D. and Charnley, S.B.: 1998, "HNC and HCN in Comets", *Astrophys. J. Lett.*, **501**, L227–L230

Wink J., Bockelée-Morvan D., Despois, D. et al.: 1997–1999, "Evidences for extended sources and temporal modulations in molecular observations of C/1995 O1 (Hale-Bopp) at IRAM interferometer", *Earth, Moon, and Planets*, **78**, 63