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Chemical diversity in the comet population

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Abstract. For the last 3 decades, infrared and microwave techniques have enabled the detection of up to 27 parent molecules in the coma of comets. Several molecules have been detected in over 40 different comets. A large diversity of composition is seen in the sample, comprising comets of various dynamical origins. Abundances relative to water for the molecules can vary by a factor 3 to more than 10. The taxonomic study of a sample of comets in which the abundance of several molecules (e.g., HCN, CH_3OH, CO, CH_4, C_2H_6, H_2S, H_2CO, CH_3CN, CS,...) has been measured does not show any clear grouping. Except for fragments of a common parent comet, every observed comet shows a different composition. The absence of any clear correlation between the volatile content of the comets and their dynamical origin (Kuiper Belt versus Oort Cloud) is consistent with a common origin for these two populations. Their diversity in composition may also suggest that radial and temporal mixing in the early proto-planetary nebula may have played an important role.

Keywords. comets: general,infrared: solar system,radio lines: solar system

1. Introduction

Comets are the most pristine remnants of the formation of the Solar System. Investigating the composition of cometary nuclei ices provides clues to the physical conditions and chemical processes at play in the primitive solar nebula. Comets may also have played a role in the delivery of water and organic material to the early Earth (Hartogh *et al.* 2011). The first taxonomy studies concerning the composition of the comets has been done (and his pursuing) by A'Hearn *et al.*(1995) on the basis of visible spectroscopy of the comets, sampling OH, CN, C_2, C_3 and NH radicals. Here we will focus on observations at longer wavelengths which probe the vibrational and rotational lines of the parent molecules, i.e., directly escaping from the sublimation of nuclear ices.

2. Infrared and radio observation of comets

During the past 10-20 years, the infrared and radio techniques made significant steps forward. The high spectral resolution in the infrared ($\lambda/\delta\lambda > 20\,000$) is necessary to isolate the narrow cometary lines from telluric absorption whereas in the millimeter to submillimeter domain the very high spectral resolution ($\lambda/\delta\lambda > 10^6$) enables the resolution of the velocity structure of the line to derive the gas expansion velocity and outgassing pattern. The recent achievements in the infrared and radio have been the extension of the instantaneous frequency coverage with the multiple order echelle spectrographs (e.g. NIRSPEC at Keck II telescope or CRIRES at VLT), and wide-band receivers coupled to fast Fourier-transform spectrometers in the radio, covering several GHz of bandwidth. Combined with an increased sensitivity of the instruments, these enable the simultaneous observations of lines of several molecular species and derive more precise relative abundances in the atmosphere of the comets. Figure 1 shows the sample of comets and

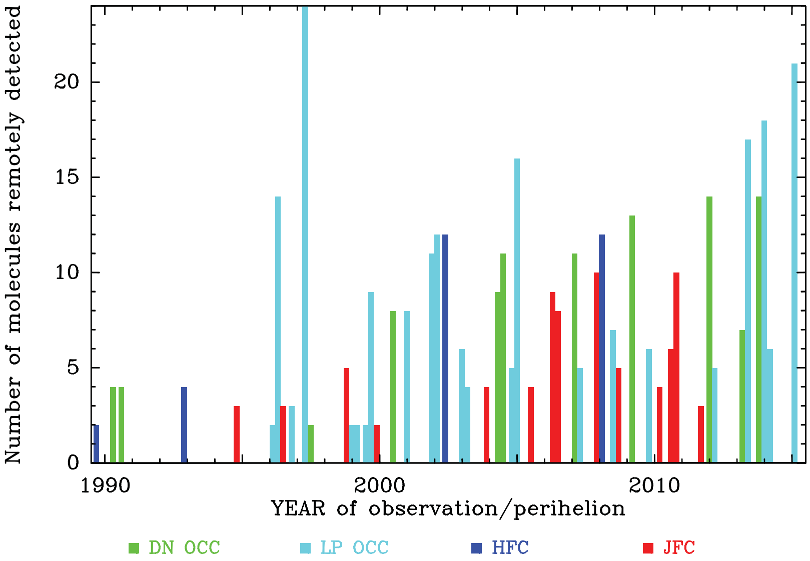

Figure 1. Number of molecules detected at infrared to radio wavelengths in each comet since 1990. Jupiter-family comets are in red, Halley-family comets in dark blue, long-period dynamically old and new comets are in light blue and green, respectively.

number of molecules observed in the IR to radio domains. We can notice that there is a deficiency in detections of a large number of molecules in Jupiter-family comets, due to their average lower activity level.

3. Molecules in cometary comae

Thanks to the increased sensitivity of the instruments, we now regularly observe a growing number of molecules in each comet, which will help to compare comets and try to infer some taxonomic grouping. In 1997, about 25 molecules were detected in the great comet Hale-Bopp. It has been since possible to observe all these molecules in at least one more comet and even two new cometary molecules were recently identified in comet C/2014 Q2 (Lovejoy) (Biver *et al.* 2015). Table 1 provides the list of the 27 molecules (other than H_2O) identified in comets and the range of abundances relative to water that has been measured.

4. Molecules with an unusual behavior

CO is one of the most volatile cometary molecule and can escape from the nucleus far from the Sun, beyond the distance at which water can sublime. So its abundance relative to water must be investigated with caution as comets initially rich in CO might become CO-depleted, as this is likely the case for Jupiter-family comets. In 2011–2012 comet C/2009 P1 (Garradd) actually showed a CO/H_2O ratio varying with time independently of the heliocentric distance (Feaga *et al.* 2014). CO_2, only observed from space, might also behave the same way and is also overabundant in comae far from the Sun (Ootsubo *et al.* 2012). HNC is unlikely a parent cometary molecule but likely produced in the coma as suggested by maps (Cordiner *et al.* 2014) and the strong dependence of its abundance with heliocentric distance (Lis *et al.* 2008). Therefore HNC cannot be considered for taxonomic studies.

Table 1. Range of abundances relative to water (in %) of molecules detected in comets.

Abundances relative to water (%), technique used: U = ultraviolet, I = infrared, R = radio (20–600 GHz)								
CHO molecules (∼ 4%)			Nitrogenous molecules (∼ 1%)			Sulfureted molecules (∼ 1.5%)		
CH_3OH	0.6–6.2	I,R	HCN	0.08–0.25[a]	R,*I*[a]	H_2S	0.13–1.5	R
H_2CO	0.13–1.4	I,R	HNC	0.002–0.035	R	OCS	0.03–0.40	I,R
HCOOH	0.028–0.18	R	HNCO	0.009–0.08	R	H_2CS	0.009–0.09	R
$(CH_2OH)_2$	0.07–0.35	R	CH_3CN	0.008–0.036	R	CS	0.02–0.20	U, R
$HCOOCH_3$	0.07–0.08	R	HC_3N	0.002–0.068	R	SO	0.04–0.30	R
CH_3CHO	0.047–0.08	R	NH_2CHO	0.008–0.021	R	NS	0.006–0.012	R
CH_2OHCHO	0.016	R	NH_3	0.3–0.7	I,R	S_2	0.001-0.25	U
C_2H_5OH	0.12	R						
C-O molecules			hydrocarbons (∼ 2%)					
CO	0.2–23	U,I,R	CH_4	0.12–1.5	I			
CO_2	2.5–30	*U*,I	C_2H_6	0.14–2.0	I			
			C_2H_2	0.04–0.5	I			

[a]: HCN is also commonly observed in the infrared, but abundances tend to be 2–3 times higher. References to individual measurements and previous reviews can be found in the Reference section.

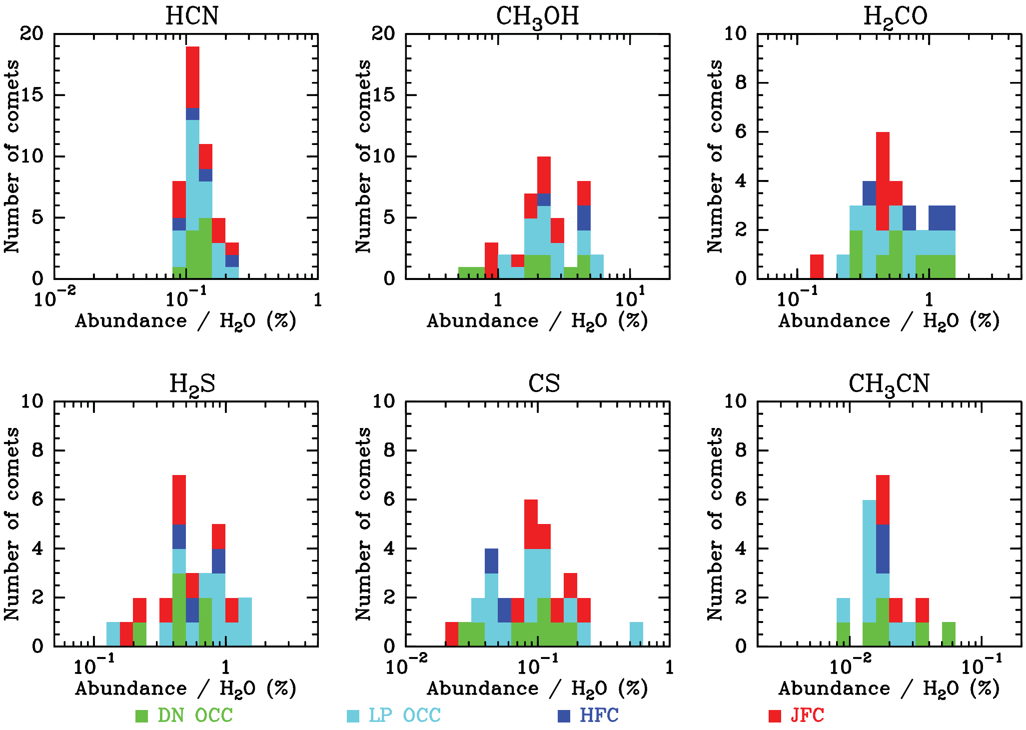

Figure 2. Histograms of the abundances relative to water (in %) of molecules observed in more than 20 comets. Jupiter family comets are in red, Halley family comets in dark blue, long period dynamically old and new are in light blue and green respectively.

5. Composition diversity

The ultimate objective of these study would be to discern grouping of comets according to their composition. Our initial attempt based on a dozen of comets and 6 molecules observed in the radio and infrared did not yield any statistically very significant sub-groups. The only exception is the two fragments B and C of comet 73P observed in 2006 which revealed a similar composition (Dello Russo *et al.* 2007). This is on the other hand an indication that comets might be homogeneous in composition. Figures 2,3 show the

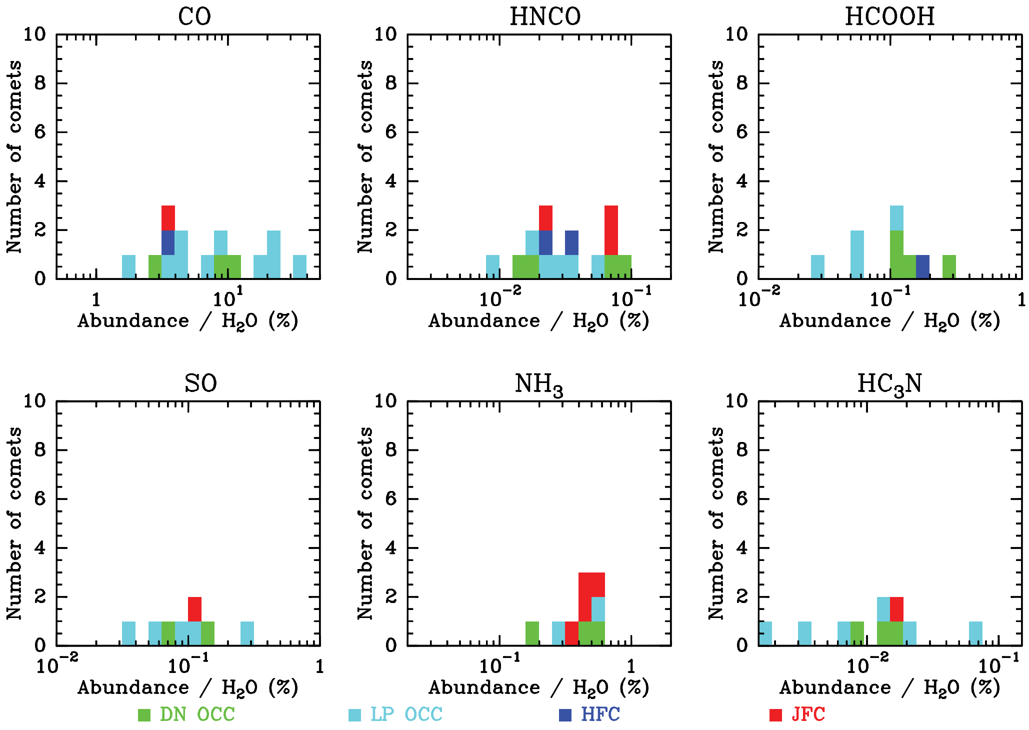

Figure 3. Same as Fig. 2: five other parent molecules and SO (being assumed to be produced from the photodissociation of SO_2) observed at radio wavelengths in more than 8 comets.

dispersion of the abundances for 12 molecules in the full sample of comets observed until 2015. The various colors correspond to different dynamical groups. When the sample gets larger (e.g. molecules of Fig. 2) the distribution of abundances seem to get closer to a Gaussian distribution with no grouping of comets according to their dynamical origin. There is a clear dispersion in abundances, which can be larger than one order of magnitude, but it looks more like a continuum is present in all dynamical class of comets. This is consistent with the dynamical calculations in the frame of the Nice model which suggest that both the Oort cloud and the scattered disk of the Kuiper belt were populated with comets formed in the same regions of the Solar System (Brasser & Morbidelli 2013).

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