The chemical diversity of comets
Synergies between space exploration and ground-based radio observations

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Abstract A fundamental question in cometary science is whether the different dynamical classes of comets have different chemical compositions, which would reflect different initial conditions. From the ground or Earth orbit, radio and infrared spectroscopic observations of a now significant sample of comets indeed reveal deep differences in the relative abundances of cometary ices. However, no obvious correlation with dynamical classes is found. Further results come, or are expected, from space exploration. Such investigations, by nature limited to a small number of objects, are unfortunately focussed on short-period comets (mainly Jupiter-family). But these in situ studies provide "ground truth" for remote sensing. We discuss the chemical differences in comets from our database of spectroscopic radio observations, which has recently been enriched by several Jupiter-family and Halley-type comets.

Keywords comets · radio spectroscopy · space exploration

1 Introduction

Among the fundamental questions on comets — their physical and chemical nature, their formation and evolution, their relation with the other Solar System bodies — is the issue of the possible relationship between their chemical composition and their orbits. The dynamical classes of comets point to various reservoirs. If these reservoirs are associated with different sites of formation, one would expect a diversity in the chemical composition of comets, due to different initial conditions.

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2 Available observations

Radio spectroscopy is a major tool for investigating the chemical composition of comets. We now have observations on more than 35 comets obtained with the IRAM, CSO, JCMT and SEST radio telescopes (Fig. 1). HCN, CH$_3$OH, H$_2$CO, CO, HNC, CH$_3$CN, H$_2$S and CS are molecules observed in more than 10 comets and suitable for statistical studies. Two dozens of rare species and isotopes are observed only in a few comets (especially in C/1995 O1 (Hale-Bopp)). The inventory of cometary molecules and their relative abundances were reviewed by Bockelée-Morvan et al. (2005).

Fig. 1 Number of molecules, radicals and ions (excepted OH, H$_2$O and isotopologues) detected by radio spectroscopy as a function of the **figure of merit** $Q/[H_2O]/\Delta$ (where $Q/[H_2O]$ is the water production rate in units of $10^{28}$ molecules s$^{-1}$ and $\Delta$ is the distance to the observer in AU). This figure of merit, which is roughly proportional to the observed signal, is convenient for comparing Earth-based radio observations for different comets. Only a selection of comets are identified by names to avoid overburdening the figure.

The water production rate of comets provides a standard for monitoring cometary activity and a reference for relative abundances in nuclear ices. Indirect measurements can be performed from the ground with the 18-cm lines of OH. About 100 comets (40 comets since 2000) were thus observed with the Nançay radio telescope (Crovisier et al., 2002, 2008). Direct measurements are possible from space with the 557 GHz line of H$_2$O. This line was observed in several comets by SWAS (Neufeld et al., 2000) and 12 comets by the Odin satellite in 2001–2006 (Lecacheux et al., 2003; Biver et al., 2007b).
Further studies of water lines are expected with the Herschel Space Observatory, to be launched in 2009 (Crovisier, 2003; Lellouch et al., this workshop).

The conditions of study are quite different for radio observations and for the space exploration of comets (Crovisier, 2007; Crovisier et al., 2009). On the one hand, Jupiter-family comets are weak and difficult to observe from the ground (with the exception of comets in undergoing outburst and comets coming close to the Earth). On the other hand, space exploration is limited to short-period, ecliptic comets (a notable exception is 1P/Halley, which was explored at the price of a large flyby velocity). This introduces observational bias with respect to the different families of comets.

3 Recent case studies

3.1 Short-period comets

Our sample of comets was recently enriched by several Jupiter-family comets. 9P/Temple 1 was the topic of a deep search for molecules as part of the international campaign of observations in support to the Deep Impact mission (Biver et al., 2007a). 73P/Schwassmann-Wachmann 3, a fragmented comet, was observed in Spring 2006 when it came at only $\Delta \approx 0.08$ AU to the Earth; its two main fragments B and C were found to have identical composition (Biver et al., 2008a; Lis et al., 2008). 17P/Holmes was observed in October–November 2007 following its huge outburst; the isotopic ratios of C, N and S could be investigated (Biver et al., 2008b; Bockelée-Morvan et al., 2008). In addition, 8P/Tuttle, a Halley-family comet that came close to the Earth, was observed in December 2007–January 2008 (Biver et al., 2008c).

3.2 Comets observed close to the Sun

Comets at small solar elongations are difficult or even impossible to observe in the visible/IR from ground-based telescopes or with spacecraft (except coronagraphs). Space observatories have a typical constraint $60^\circ < \text{solar elongation} < 120^\circ$. This is a strong penalty for cometary observations since comets are brighter close to the Sun (a heliocentric distance $r_h < 0.20$ AU corresponds to a solar elongation $< 11.5^\circ$).

However, observations at small solar elongations are possible with some radio telescopes (e.g., Nançay radio telescope, IRAM 30-m telescope, ALMA). They allow us to investigate: 1) gas velocity and temperature; 2) specific mechanisms such as photolysis shielding; 3) high-temperature sublimation regimes, and to search for refractories. Recently, observations at IRAM allowed us to investigate C/2002 X5 (Kudo-Fujikawa) at $r_h = 0.21$ AU, C/2002 V1 (NEAT) at 0.11 AU and C/2006 P1 (McNaught) at 0.21 AU (Biver et al., 2008d, 2009).

4 Chemical diversity and taxonomy

Our preceding analysis of the chemical diversity of comets from radio studies was based upon $\approx 20$ comets (Biver et al., 2002). Our sample is now extended to more than 35 comets. Fig. 2 shows the histograms of the relative abundances of various molecules. With the exception of HCN, there are large variations from comet to comet.
Fig. 2 Histograms of molecular abundances relative to water from the radio observations of \( \approx 30 \) comets. The black part of the histograms pertains to Jupiter-family comets, the grey part (red part in the electronic version) to Oort-cloud comets (long-period and Halley-type).

For instance, the distribution of methanol is spread over a factor of ten. There is no clear evidence, however, for the existence of three distinct classes of comets ("normal", "enhanced" or "depleted" in organics), which were proposed by Mumma et al. (2008, and this workshop) from infrared spectroscopy of a smaller sample of comets. Fig. 2 also shows the abundance histograms separately for Jupiter-family comets and the other comets. Although the Jupiter-family comets are under-represented in the sample, there is no indication of a different distribution for this class of comets (Crovisier, 2007; Crovisier et al., 2009).

5 Conclusions

- The cometary diversity can only be studied by large ground-based or Earth-orbit observing programmes. Space exploration accesses only a limited number of objects among short-period comets.
- Space exploration provides "ground truth" for remote sensing observations by assessing the link between nucleus ices and coma species.
- Radio spectroscopy (as well as visible and IR spectroscopy) reveals a broad chemical diversity among comets.
- There is no obvious correlation between chemical diversity and the dynamical classes of comets.
- Future prospects for radio studies of comets include observations with increased sensitivity from the ground with ALMA (Bockelee-Morvan, 2008) or from space with the Herschel Space Telescope (Crovisier, 2005, Lellouch et al., this workshop) and in situ detailed investigations with Rosetta/MIRO (Gulkis et al., 2007).
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