COMETS AT SUBMILLIMETRIC WAVELENGTHS

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ABSTRACT

We review the present status of cometary observations at submillimetric wavelengths and their prospect in the context of future projects such as FIRST. Radio astronomy is a privileged tool to study the composition and physical properties of comets, the submillimetric domain being especially interesting. This was fully demonstrated by the recent observations of two exceptional comets: C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp) with most of the major radio telescopes, including submillimetric studies with the James Clerk Maxwell Telescope (JCMT) and the Caltech Submillimeter Observatory (CSO). Hale-Bopp was also observed in the far-infrared by the Infrared Space Observatory (ISO) as a target of opportunity. Several new species were detected at submillimetric wavelengths: HNC, $H^{13}CN$, HNCO, H_3O^+... and especially HDO, allowing the first remote-sensing determinations of the [D]/[H] ratio in a comet. Dust studies through submillimetric continuum radiation allow us to sample the large-size particles and to complete our knowledge of the cometary dust population. There are several future space projects related to the submillimetric investigation of comets. The small space radio telescope ODIN will have a channel dedicated to the 557 GHz line of water and is expected to observe this line in several comets. Aboard the ROSETTA space probe, MIRO (Microwave Instrument for Rosetta Orbiter) is a small radio telescope with continuum and spectroscopic channels. With a 3-metre antenna and tunable receivers covering the whole submillimetric range, FIRST will be able to extend these studies with unprecedented sensitivity and to search for several new cometary molecules.

1. INTRODUCTION

Radio astronomy has now proved to be a major tool for studying comets. It can address the composition of cometary ices by identifying the volatile molecules released in the coma. Most of the known species were identified by radio spectroscopy, some of them with abundances relative to water of 10^{-4} only. The species that escape radio studies are molecules without dipolar moments: CO_2 and hydrocarbons, rather observed in the infrared, and — ironically — water, the most abundant cometary volatile, whose rotational lines cannot be observed from the ground; planned submillimetric space facilities will fill this gap, however, and ISO did observe rotational lines of water in the far-infrared in comet Hale-Bopp.

Radio spectroscopy can also probe cometary radicals and ions. Its high spectral resolution permits investigation of the kinematics of cometary atmospheres: anisotropic outgassing of the nucleus, hydrodynamics of the inner coma, and evolution of the coma under the influence of photolytic processes and interaction with solar wind (Fig. 1). The kinetic temperature of cometary atmospheres can be evaluated by measuring the rotational temperature of selected molecules through the observation of several of their rotational lines (Fig. 2). This provides us with a unique information requested for the interpretation of all spectral data and their conversion into column densities and molecular abundances.

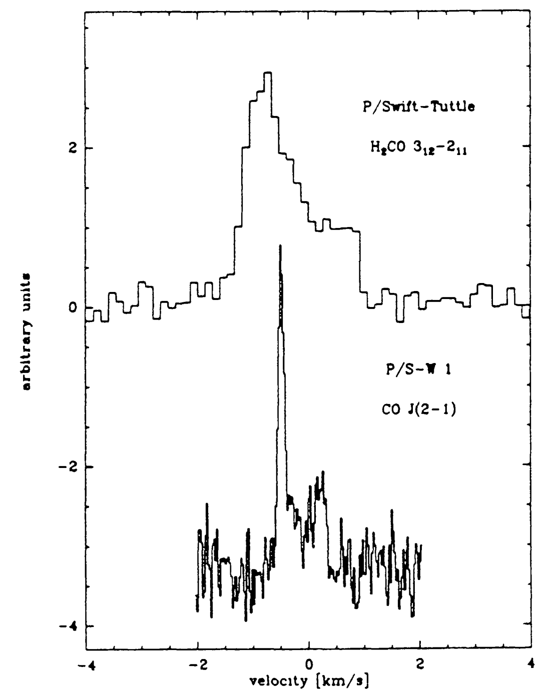

Figure 1: Two extreme examples of radio line profiles observed with the IRAM 30-m probing the kinematics of the coma. Top: the 3_{12}-2_{11} formaldehyde line in 109P/Swift-Tuttle at r = 1 AU; at this distance, strong sunward jets were present and the coma had a high expansion velocity [Ref. 10]. Bottom: the J(2-1) carbon monoxide line in 29P/Schwassmann-Wachmann 1 at r = 6 AU; the coma was very cold, probably less than 10 K to explain the very narrow feature of 0.14 km s^{-1} width at negative velocities, and the expansion velocity was small [Ref. 8].

Continuum observations at radio wavelengths probe the large-size dust particles, in contrast to infrared and vi-

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sible observations which are sensitive to smaller particles. They are thus complementary for the knowledge of the dust size distribution in comets.

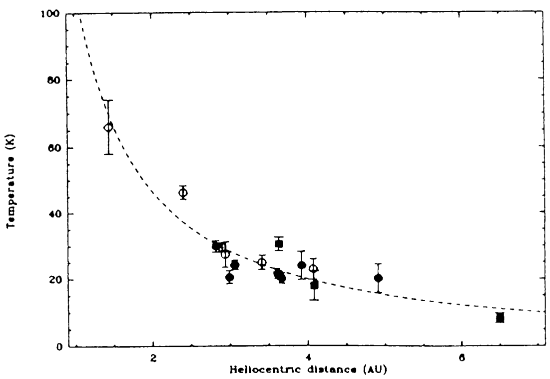

Figure 2: Evolution of the temperature measured in the coma of comet Hale-Bopp as a function of the heliocentric distance. The temperature is derived from the CO lines (115, 230, 345 and 460 GHz) or the CH_3OH lines (groups at 157 or 252 GHz, or 304/307 GHz pair). (IRAM and JCMT observations, from [Ref. 2].)

The millimetric and submillimetric domains appear to be complementary for cometary observations. This is due to the large range of rotational temperatures that can be encountered — from less than 10 K at a heliocentric distance $r \approx 6$ AU to 100 K or more at $r \approx 1$ AU (Fig. 2) and to the diversity of molecules to be investigated — from light hydrides like H_2O, H_2O^+ or H_3O^+ which have their fundamental rotational lines uniquely in the submillimetric to heavy molecules like HC_3N or OCS which have their strongest lines in the millimetric. Investigating the rotational distribution of molecules and the continuum spectrum of dust also requires a large spectral dynamics.

2. MILESTONES IN COMETARY RADIO ASTRONOMY

In contrast with the inventory of interstellar molecules by radio spectroscopy in the last three decades, the first progresses of cometary radio astronomy were rather slow. After the detection of the OH lines at 18 cm in comet Kohoutek in 1973, of HCN in comet Halley in 1985, only half a dozen molecules were observed by their radio lines in comets at the beginning of 1996 (Table 1). The submillimetric domain was first unravelled in comets with the observations of C/1990 K1 (Levy) in 1990 at the CSO [Ref. 18] and 109P/Swift-Tuttle in 1992 at the JCMT [Ref. 5].

Comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp) were two exceptional comets recently offered to our investigations. The first one — only five times less productive than P/Halley when observed at $r \approx 1$ AU — passed at only 0.1 AU from the Earth at the end of March 1996. The second was ten to one hundred more productive than P/Halley at the same heliocentric distances; it was discovered at $r \approx 7$ AU, allowing a detailed study of the evolution of the comet activity as it approached to 0.91 AU to the Sun on 1 April 1997.

Table 1: Chronology of first detections of radio lines in comets.

1973	Kohoutek	OH, HCN ?
1983	IRAS-A-A	NH_3 ?
1986	P/Halley	HCN, H_2CO ?
1990	Austin, Levy	H_2CO, H_2S, CH_3OH
1994	P/S-W 1	CO
1996	Hyakutake	CS, NH_3, HNC, HDO, CH_3CN, OCS ? HNCO ?
1997	Hale-Bopp	OCS, HNCO, HC_3N, SO, SO_2, HC_2S, HCOOH, NH_2CHO, CN, CO^+, HCO^+, H_3O^+

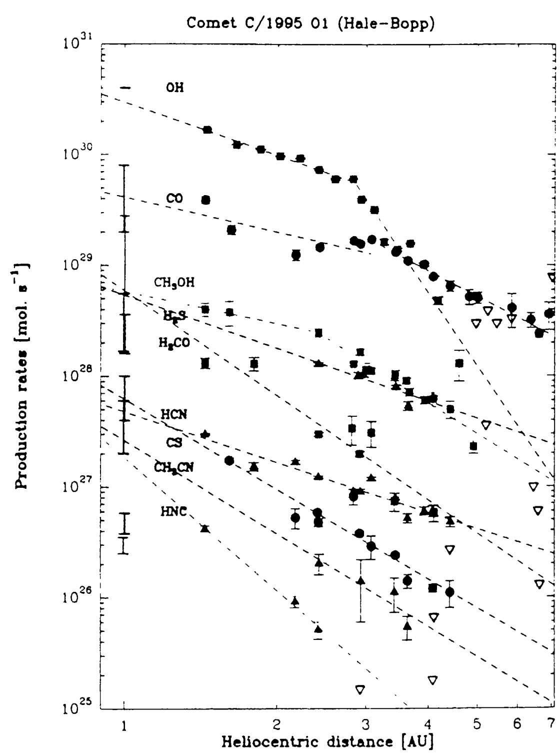

Figure 3: Evolution of the molecular production rates with heliocentric distance observed pre-perihelion in comet Hale-Bopp with the Nançay radio telescope (OH), the IRAM 30-m and the JCMT. From [Ref. 2].

3. RECENT RESULTS

A dozen new constituents of cometary ices were identified at least in comets Hyakutake and Hale-Bopp from radio spectroscopy (Table 1), complemented by several hydrocarbons from infrared spectroscopy [Ref. 7, 16].

This makes now a fairly comprehensive view of the composition of cometary ices (Table 2). Probably, the most abundant species are now known (although several species such as O_2, H_2 or N_2 escape spectroscopic detection). The composition of cometary ices is strikingly similar (at least qualitatively) to that of interstellar ices (as known from infrared observations, ISO and others).

Table 2: Molecular abundances of cometary volatiles.

molecule	abundance$^{a)}$	method	N$^{b)}$	comments	references
H_2O	100.	IR	6	also indirect (from OH, O, H)	[4, 9], IAUC 6604
HDO	0.05	radio	2		[6], IAUC 6615
CO	2–20.	UV, radio, IR	> 5	extended source?	[4]
CO_2	2–6.	IR	2		[4, 9]
H_2CO	0.05–4.	radio	> 5	extended source	[4]
CH_3OH	1–7.	radio, IR	> 5		[4]
HCOOH	~ 0.1	radio	1		IAUC 6599
HNCO	0.07	radio	2		[15], IAUC 6566
NH_2CHO	~ 0.1	radio	1		IAUC 6614
CH_4	0.7	IR	2		[16], IAUC 6573
C_2H_2	0.3–0.9	IR	2		[7], IAUC 6573
C_2H_6	0.4	IR	2		[16], IAUC 6573
NH_3	0.5	radio	3	also indirect (from NH, NH_2)	[4], IAUC 6607
HCN	0.1–0.2	radio, IR	> 5		[4]
HNC	0.01	radio	2		[2, 12]
CH_3CN	0.01	radio	2		[4], IAUC 6458
HC_3N	0.01	radio	1		IAUC 6566
H_2S	0.3	radio	> 5		[4]
H_2CS	0.01	radio	1		IAUC 6607
CS	0.1	UV, radio	> 5	from CS_2?	[4]
OCS	0.3	radio	2		[4], IAUC 6573, 6607
SO	~ 0.5	radio	1	from SO_2?	IAUC 6573
SO_2	~ 0.1	radio	1		IAUC 6591
S_2	0.005–0.2	UV	2		[4]

a) abundance relative to water (100).
b) number of comets in which this species was reliably and directly observed.

Especially significant is the evolution of the production rates of various volatiles observed from $r = 7$ to 1 AU in comet Hale-Bopp (Fig. 3). Far from the Sun, CO is the main volatile driving cometary activity [Ref. 3, 14] (as was already found in comet 29P/Schwassmann-Wachmann 1 [Ref. 8, 19]). This role is progressively transferred to water as the comet approaches the Sun. This reflects the differences in volatility of H_2O and CO. The other species show various behaviours as a function of r, which are not directly linked to their volatility, and which suggest that the sublimation of cometary ice is a complex process [Ref. 2].

Many sulphurous species are now known: in addition to CS_2 (traced by CS), H_2S and S_2, were recently detected OCS, H_2CS and the couple SO, SO_2. The detection of these two latter came as a surprise, because stringent upper limits were put on previous comets from UV spectra.

Since HCN — the first parent molecule observed at radio wavelengths in a comet — several other nitriles have been detected: HNC, CH_3CN, HC_3N. Isocyanic acid (HNCO) has also been found, which might be linked to the mysterious "XCN" species observed in interstellar ices, as well as formamide (NH_2CHO). Of peculiar interest is the [HNC]/[HCN] ratio observed in comets: it was 6% in comet Hyakutake (Fig. 4), which cannot be explained by thermal equilibrium reactions. It is, however, in the range of ratios observed in quiescent interstellar clouds, tightening the link between interstellar and cometary matter [Ref. 12]. In comet Hale-Bopp, however, the [HNC]/[HCN] ratio was found to increase as the comet approached the Sun, from less than 3% to 20% or more [Ref. 2]. One would expect that HNC and

HCN, if uniformly mixed in cometary ices, would give a constant [HNC]/[HCN] ratio in the coma, and the mechanism responsible for a varying ratio is still to be found.

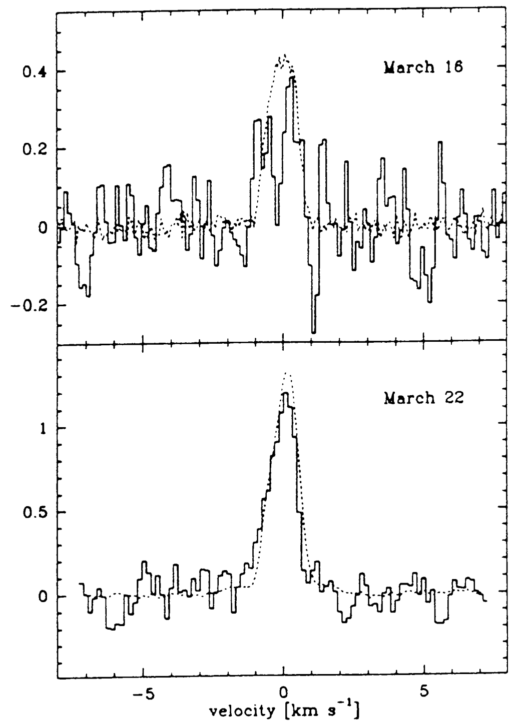

Figure 4: The *J*(4-3) line of HNC (solid lines) and the corresponding line of HCN (dashed lines, multiplied by 0.1) observed at the JCMT (top) and at the CSO (bottom) in comet Hyakutake. From [Ref. 12].

The lines of several ions have been observed in comet Hale-Bopp: CO^+, HCO^+ and H_3O^+. This will help us to understand the complex ion-neutral chemistry which takes place in the coma. The line shapes will also allow us to track the MHD interaction between cometary ions and the solar wind.

Rare isotopic species have now been observed from millimetric and submillimetric lines. $[^{13}C]/[^{12}C]$, $[^{15}N]/[^{14}N]$ and $[^{34}S]/[^{32}S]$ are found "normal" from HCN and CS. HDO has been observed from its 1_{10}-0_{00} line at 465 GHz in comet Hyakutake at the CSO (Fig. 5) and with the JCMT in comet Hale-Bopp. A ratio [D]/[H] $\approx 3 \times 10^{-4}$ has been derived for cometary water in comet Hyakutake [Ref. 6], which is in agreement with the value derived from in situ mass spectroscopy in P/Halley. This shows an important enrichment over the [D]/[H] values for the local interstellar medium ($\approx 1.5 \times 10^{-5}$) and the protosolar nebula ($\approx 3 \times 10^{-5}$). It is even larger than the Earth oceans values ($\approx 1.5 \times 10^{-4}$). Since important deuterium enrichments are also found for several interstellar molecules, including water, this provides evidence that cometary ices could have formed from interstellar grain mantles.

Comet Hale-Bopp was observed by ISO in April and September-October 1996 [Ref. 9]. The spectrum of water was observed at high resolution through its vibrational bands in the 2.6-2.9 μm region (ν_1, ν_3 and combination bands). This will permit a detailed study of the excitation conditions of this molecule and of its ortho-to-para ratio. In the far-infrared, two rotational transitions of water were detected with the long-wavelength spectrometer of ISO (Fig. 6). These lines were predicted to be the strongest cometary lines in this spectral domain. They are optically thick, but they play an important role in the thermal balance of cometary atmospheres.

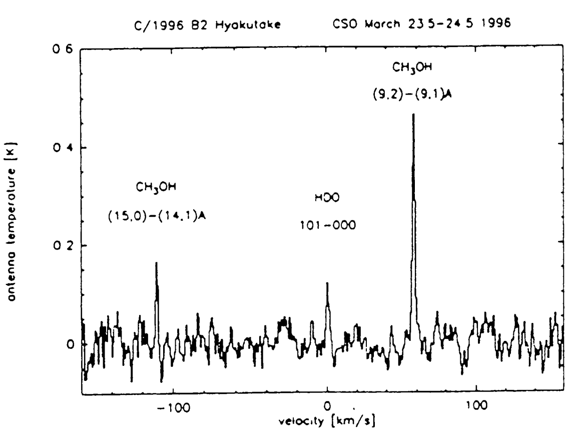

Figure 5: The 1_{10}-0_{00} HDO line at 465 GHz observed at the CSO in comet Hyakutake. Two lines of CH_3OH are present in the same spectrum. From [Ref. 6].

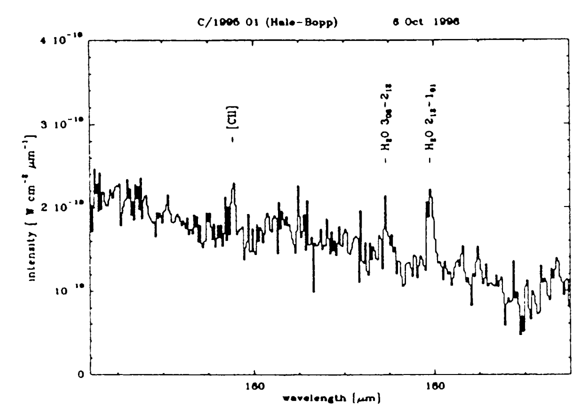

Figure 6: The rotational lines of water observed by the ISO long-wavelength spectrometer in comet Hale-Bopp at r = 2.9 AU on 6 October 1996. The [CII] line is due to background interstellar emission. From [Ref. 9].

Continuum observations of comets at radio wavelengths are a difficult task because of the weakness of the signal, unless the comet is exceptionally bright or passes close to the Earth. Detection is easier in the submillimetric rather than in the millimetric range, because in these domains, comets are Rayleigh-Jean emitters. Since the observations of P/Halley [Ref. 1], it is known that the signal is dominated by emission of large-size particles rather than that of the nucleus. Only in recent observations of comet Hale-Bopp with the IRAM Plateau de Bure interferometer was it possible to separate nucleus from dust emissions [Ref. 20] (and to infer a nucleus diameter of $\approx$ 45 km for this comet). For comet Hyakutake, the continuum spectrum was observed from 0.35 to 2 mm with the JCMT (Fig. 7) [Ref. 13]. The spectrum departs from a blackbody spectrum with an opacity index $\beta = 0.89 \pm 0.10$, which suggests that submillimetric emission is dominated by large (radii > 1 mm) particles. This index is consistent with those observed in the circumstellar discs of T Tauri stars.

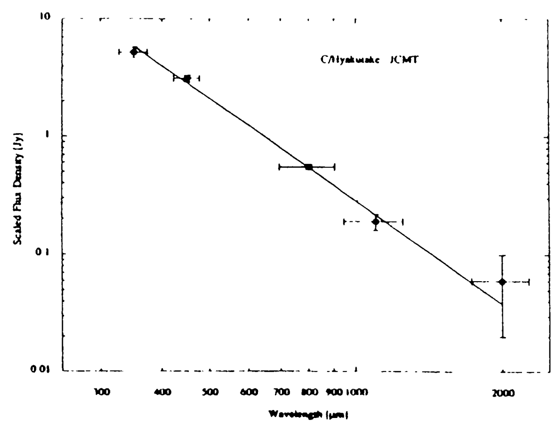

Figure 7: The continuum spectrum of comet Hyakutake observed by the JCMT in the submillimetre domain. The data were taken on 23-24 March 1996 when the comet was at 1.07 AU from Sun and 0.11 AU from Earth. From [Ref. 13].

Thermal emission of comet Hale-Bopp in the 7-45 μm region, as observed by ISO [Ref. 9] shows strong bands in addition to blackbody emission. They were identified to the presence of crystalline Mg-rich olivine (forsterite) in cometary dust. A similar material was found in the circumstellar discs of Vega-type stars.

4. FUTURE PROSPECTS

Recent ground-based observations (complemented by the far-infrared, non-heterodyne observations of ISO) have fully demonstrated the interest of submillimetric observations of comets, their idiosyncrasy, and their complementarity to observations at other wavelengths. Due to the limited observing time of these events, the recent observations of the two exceptional objects Hyakutake and Hale-Bopp are far from having exhausted the interest of this specific spectral domain. They will have to be resumed on future bright comets and even on medium-bright comets for investigating the diversity of these objects.

However, ground-based observations are hampered by telluric absorption: some spectral ranges are completely absorbed (this is the case for the water lines) and others can only be observed under exceptional weather conditions with degraded performances. Space facilities are definitely needed. Space projects related to submillimetric investigations of comets are examined below.

ODIN is a small 1.1-m diameter submillimetric telescope dedicated to aeronomic and astronomical observations, to be launched in 1998 [Ref. 17]. One of its receivers is to observe the 1_{10}-1_{01} water line at 557 GHz with good spectral resolution. Among its main scientific programs are the observation and monitoring of this water line in several comets (periodic comets such as 21P/Giacobini-Zinner as well as unexpected comets which could appear during its 2-year life-time).

ROSETTA is an ESA mission to be launched towards comet 46P/Wirtanen in 2003. It will meet the comet at $r \approx 3.8$ AU in May 2012 and accompany it until perihelion at 1.05 AU in July 2013. Among the remote-sensing instruments of the probe is MIRO, a microwave experiment [Ref. 11]. MIRO is to be equipped with continuum and spectroscopic channels at millimetre and submillimetre wavelengths. Radiometric observations of the nucleus will determine its surface temperature and thermal gradient. Lines of selected molecules (water and water isotopes, CO, CH_3OH...) will be observed to determine the chemical and physical properties of the coma and its relations with the active regions of the nucleus.

The FIRST mission, with a 3-m antenna and tunable receivers operating over the full submillimetric domain, will be able to extend the ground-based observations of comets, to search for several new cometary molecules, and to investigate the continuum radiation of cometary dust.

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