Radio observations of Jupiter-family comets

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Abstract

Radio observations from decimetric to submillimetric wavelengths are now a basic tool for the investigation of comets. Spectroscopic observations allow us i) to monitor the gas production rate of the comets, by directly observing the water molecule, or by observing secondary products (e.g., the OH radical) or minor species (e.g., HCN); ii) to investigate the chemical composition of comets; iii) to probe the physical conditions of cometary atmospheres: kinetic temperature and expansion velocity. Continuum observations probe large-size dust particles and (for the largest objects) cometary nuclei.

Comets are classified from their orbital characteristics into two separate classes: i) nearly-isotropic, mainly long-period comets and ii) ecliptic, short-period comets, the so-called Jupiter-family comets. These two classes apparently come from two different reservoirs, respectively the Oort cloud and the trans-Neptunian scattered disc. Due to their different history and — possibly — their different origin, they may have different chemical and physical properties that are worth being investigated.

The present article reviews the contribution of radio observations to our knowledge of the Jupiter-family comets (JFCs). The difficulty of such a study is the commonly low gas and dust productions of these comets. Long-period, nearly-isotropic comets from the Oort cloud are better known from Earth-based observations. On the other hand, Jupiter-family comets are more easily accessed by space missions. However, unique opportunities to observe Jupiter-family comets are offered when these objects come by chance close to the Earth (like 73P/Schwassmann-Wachmann 3 in 2006), or when they exhibit unexpected outbursts (as did 17P/Holmes in 2007).

About a dozen JFCs were successfully observed by radio techniques up to now. Four to ten molecules were detected in five of them. No obvious evidence for different properties between JFCs and other families of comets is found, as far as radio observations are concerned.

Key words:
comets, radio observations, spectroscopy

1. Introduction

Jupiter-family comets (JFCs, aka *ecliptic comets*) are short-period, low-inclination comets likely to undergo orbital perturbations by Jupiter. We adopt here the definition based on the Tisserand invariant with respect to Jupiter T_J: JFCs are comets for which $2 < T_J < 3$ (Levison, 1996). Special cases are 2P/Encke which slightly exceeds the $T_J = 3$ limit and for this reason sometimes classified as a *Encke-type* comet, and 29P/Schwassmann-Wachmann 1 with $T_J = 2.99$, alternatively classified as a *Centaur*. JFCs are believed to come from the trans-Neptunian scattered disc. They contrast with the *nearly isotropic comets*, which comprise long-period comets as well as short-period comets (the so-called *Halley type comets*), supposed to come from the Oort cloud. Comets certainly did not form in these trans-Neptunian reservoirs. Their real sites of formation and their orbital evolution are still highly debated topics. (For reviews on cometary families and their dynamical evolution, see Levison (1996); Fernández (2008); Lowry et al. (2008); Morbidelli (2008); Morbidelli et al. (2008); Marsden (2008)). Having different dynamical histories and — possibly — different origins, these distinct classes of comets may have different chemical and physical properties that are worth being investigated.

JFCs and other comets are far from being equally well observed. To show this for Earth-based observations, we will use the *figure of merit* parameter $FM = Q_{\mathrm{H_2O}}/\Delta$, where $Q_{\mathrm{H_2O}}$ is the water production rate in units of 10^{28} s^{-1} and Δ is the distance to the observer in AU. (Note that this parameter differs from the *figure of merit* introduced

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Table 1
Remote sensing observing conditions for a selection of comets

comet	date	r_h [AU]	Δ [AU]	Q_{H_2O} [10^{28} s^{-1}]	FM
Nearly-isotropic comets					
C/1986 P1 (Wilson)	May 1987	1.3	1.0	12	12
C/1989 X1 (Austin)	April 1990	1.2	0.25	2.5	10
C/1990 K1 (Levy)	August 1990	1.3	0.45	25	55
C/1996 B2 (Hyakutake)	March 1996	1.1	0.11	25	225
C/1995 O1 (Hale-Bopp)	April 1997	0.9	1.4	1000	700
C/1999 S4 (LINEAR)	July 2000	0.77	0.38	10	25
C/1999 T1 (McNaught-Hartley)	December 2000	1.2	1.6	10	6
C/2001 A2 (LINEAR)	June 2001	1.0	0.24	10	40
C/2000 WM_1 (LINEAR)	December 2001	1.2	0.32	4	12
C/2001 Q4 (NEAT)	May 2004	1.0	0.32	20	60
C/2002 T7 (LINEAR)	May 2004	0.8	0.27	10	25
C/2003 K4 (LINEAR)	December 2004	1.4	1.2	15	12
C/2004 Q2 (Machholz)	January 2005	1.2	0.35	25	70
Halley-type comets					
1P/Halley	January 1986	0.7	1.5	120	80
109P/Swift-Tuttle	November 1992	1.0	1.3	50	40
153P/2002 C1 (Ikeya-Zhang)	April 2002	1.0	0.40	25	60
8P/Tuttle	January 2008	1.1	0.25	3	12
Jupiter-family comets					
22P/Kopff	April 1996	1.7	0.9	3.5	4
21P/Giacobini-Zinner	October 1998	1.2	1.0	3	3
19P/Borrelly	September 2001	1.36	1.47	3	2
2P/Encke	November 2003	1.0	0.25	0.5	2
9P/Tempel 1	July 2005	1.5	0.77	1	1.3
73P/Schwassmann-Wachmann 3	May 2006	1.0	0.08	2	25
17P/Holmes	October 2007	2.4	1.6	> 100	> 60
67P/Churyumov-Gerasimenko	Mars 2009	1.24	1.7	1	0.6
103P/Hartley 2	October 2010	1.1	0.12	1.2	10
45P/Honda-Mrkos-Pajdušáková	August 2011	1.0	0.06	0.5	8

Date is for best observing conditions.
r_h = distance to Sun and Δ = distance to Earth at that date.
Q_{H_2O} = water production rate at that date.
$FM = Q_{H_2O}/\Delta$ = *figure of merit*, roughly proportional to the signal of cometary molecules.

by Mumma et al. (2002), which includes a dependency on the distance to the Sun.) This parameter is roughly proportional to the expected signal intensity (for comets at heliocentric distances of the order of 1 AU), and allows us to evaluate and compare the observability of comets. Table 1 gives the figures of merit for Earth-based observations of recent long-period comets, as well as for recent and future returns of short-period comets. One can see that unexpected, long-period comets from the nearly isotropic class of comets and Halley-type comets offer much better opportunities than short-period comets. Indeed, the two best comets in the last twenty years were C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp); unprecedented spectroscopic observations leaded to the identification of many molecules for the first time in these two objects (Bockelée-Morvan et al., 2005).

All JFCs are comets with low water production rates Q_{H_2O} of at most a few 10^{28} s^{-1} at perihelion. The best observing conditions occur for these comets which make a close approach to the Earth (i.e., for Δ significantly smaller than 1 AU). This was recently the case for 73P/Schwassmann-Wachmann 3 (minimum geocentric distance $\Delta = 0.08$ AU in May 2006) and it will also hap-

pen for 103P/Hartley 2 in the near future ($\Delta = 0.12$ AU in October 2010). But the *figure of merit* of such JFCs is still lower than that of some long-period comets for which FM could exceed 50. Other unique opportunities also occur when JFCs exhibit unexpected outbursts during which the gas production rate may be increased by several orders of magnitude. This was recently the case for 17P/Holmes, but such events are rare.

On the other hand, short-period comets, with their predicted returns, are the only practicable targets for space missions, which are not yet versatile enough to accommodate unexpected comets. Flybys at a low velocity and rendezvous are only possible for ecliptic comets, due to the energy limitations of current space technology. 1P/Halley is the only explored comet which does not belong to the Jupiter family: the price to pay was a very high flyby velocity (≈ 70 km s^{-1}).

Spectroscopy at radio wavelengths is now a basic tool for the investigation of comets. It allows us:

- to monitor the gas production rate of the comets, by directly observing the water molecule, or by observing secondary products (e.g., the OH radical) or minor species (e.g., HCN);
- to investigate the chemical composition of comets;
- to probe the temperature of cometary atmospheres by observing simultaneously several rotational lines of the same molecule;
- to investigate the expansion velocity and kinematics of cometary atmospheres from the observation of line shapes.

Continuum observations of comets in the radio spectral range are also well suited for studying the nucleus and the dust coma via their thermal radiation. Since millimetric and submillimetric radiation can only be efficiently radiated from large particles ($\gtrsim 1$ mm) which comprise most of the dust mass, this technique is a useful probe of the total dust mass production and of the size distribution of the large grains.

The present article reviews the contribution of radio observations to our knowledge of JFCs. The outcome of radar experiments (Harmon et al., 2005), which probe the nucleus and large dust particles, is beyond the scope of this paper.

2. The monitoring of gas production rates

2.1. *Observations of the OH 18-cm lines*

The OH radical in comets is a photodestruction product of water, the main constituent of cometary nucleus ices. The observation of its 18-cm lines allows us to trace the production rate and the kinematics of water. These lines were first observed in comet C/1973 E1 (Kohoutek) at Nançay (Biraud et al., 1974) and Green Bank (Turner, 1974). They were subsequently systematically observed. Their excitation process is now fairly well known and the subject of extensive modelling: the cometary OH radicals act as a

Table 2
Short-period numbered comets observed at Nançay (OH 18-cm lines)

Comet	peri. year	[a)]	T_J [b)]	type[c)]
1P/Halley	1986	D	−0.61	HTC
2P/Encke	1977	–	3.03	ETC
	1980	M		
	1994	M		
	1997	–		
	2003	D		
	2007	D		
4P/Faye	2006	D	2.75	JFC
6P/d'Arrest	1982	M	2.71	JFC
8P/Tuttle	1994	M	1.60	HTC
	2008	D		
9P/Tempel 1	2005	D	2.97	JFC
15P/Finlay	1995	–	2.62	JFC
16P/Brooks 2	2001	–	2.88	JFC
17P/Holmes	2007	D	2.86	JFC
19P/Borrelly	1994	D	2.56	JFC
	2001	D		
21P/Giacobini-Zinner	1985	D	2.47	JFC
	1998	D		
22P/Kopff	1996	D	2.87	JFC
23P/Brorsen-Metcalf	1989	D	1.11	HTC
24P/Schaumasse	1993	D	2.50	JFC
	2001	M		
26P/Grigg-Skjellerup	1982	–	2.81	JFC
27P/Crommelin	1984	M	1.48	HTF
45P/Honda-Mrkos-Pajdušáková	1995	M	2.58	JFC
	2001	–		
46P/Wirtanen	1997	–	2.82	JFC
	2002	–		
	2008	D		
64P/Swift-Gehrels	1981	–	2.49	JFC
67P/Churyumov-Gerasimenko	1982	M	2.75	JFC
73P/Schwassmann-Wachmann 3	1995	D	2.78	JFC
	2001	D		
	2006	D		
81P/Wild 2	1997	M	2.88	JFC
96P/Machholz 1	2007	D	1.94	HTC
109P/Swift-Tuttle	1992	D	−0.27	HTC
122P/de Vico	1995	D	0.37	HTC
141P/Machholz 2	1994	M	2.71	JFC
153P/Ikeya-Zhang	2002	D	0.88	HTC

[a)] –: no detection; M: marginal detection; D: clear detection.
[b)] Tisserand parameter.
[c)] JFC: Jupiter-family comet; HTC: Halley-type comet; ETC: Encke-type comet.
See details on observations in Crovisier et al. (2002) and `http://www.lesia.obspm.fr/planeto/cometes/basecom/index.html`.

weak maser, whose inversion is governed by solar UV excitation. Because of coincidence of the OH exciting UV lines with Fraunhofer lines, the OH maser inversion strongly depends upon the comet heliocentric velocity (Despois et al., 1981; Schleicher and A'Hearn, 1988). Quenching by collisions, which is an efficient process in the inner coma of the most productive comets, must also be taken into account (Despois et al., 1981; Schloerb, 1988; Gérard, 1990).

Up to now (beginning of 2008), about 100 comets have been observed with the Nançay radio telescope (Despois et al., 1981; Crovisier et al., 2002, 2008, and in preparation) and with other decimetric radio telescopes. These observations include more than 30 passages of Jupiter-family comets (Tables 2 and 3). In many cases, the weak JFCs were not, or only marginally, detected (Fig. 1).

The observation of 6P/d'Arrest at the Vermilion River Observatory in 1976, at $\Delta \approx 0.2$ AU, was claimed as the first radio detection of a short-period comet (Webber and Snyder, 1977) (Fig. 2). Was this detection secure? The signal-to-noise ratio was poor, and only the 1665 MHz line showed well, in emission whereas the signal is expected in absorption (Fig. 2). The same comet was only marginally detected at its following return at Nançay (Crovisier et al., 2002). We consider that the first reliable detection of a JFC at radio wavelengths was that of 21P/Giacobini-Zinner at its 1985 passage with several radio telescopes (Norris et al., 1985; Galt, 1987; Gérard et al., 1988; Tacconi-Garman et al., 1990).

Fig. 1. Tentative detection of the OH 18-cm lines in comet 67P/Churyumov-Gerasimenko at Nançay in 1982, at $r_h = 1.35$ AU and $\Delta = 0.50$ AU. The fitted Gaussian corresponds to $Q_{\rm OH} = 0.9 \pm 0.2 \times 10^{28}$ s^{-1}. From Crovisier et al. (2002).

The typical 3–σ detection limit at Nançay is 6 mJy for a line width of 2 km s^{-1} and about 10 hours of integration. This corresponds to about $Q_{\rm OH} = 0.5 \times 10^{28}$ s^{-1} for a comet at $\Delta \approx 1$ AU at a moment of favourable maser inversion (≈ 0.40). Since the Nançay telescope can only observe a given target for ≈ 1 hr per day, the 10 hours of integration are spread over the same number of days. The Arecibo and Green Bank radio telescopes can achieve better limits with longer integration times per day (Fig. 4).

Fig. 2. The observations at the VRO of the OH 18-cm lines in 6P/d'Arrest (left panels) and in comet C/1975 V1 West (right panel). For 6P/d'Arrest, the 1665 MHz line appears in emission and the 1667 MHz is possibly in absorption whereas excitation models predict absorption for both transitions (heliocentric velocity –5.6 to –3.1 km s^{-1}). From Webber and Snyder (1977).

Fig. 3. Detection of the OH 18-cm lines in comet 9P/Tempel 1 at Nançay in March–April 2005, at $r_h = 1.76$ AU and $\Delta = 0.79$ AU. The fitted Gaussian corresponds to $Q_{\rm OH} = 0.4 \times 10^{28}$ s^{-1}. From Biver et al. (2007a). Compared to Fig. 1, this shows the improvement in sensitivity of the Nançay radio telescope.

2.2. *Observation of the 557 GHz line of water*

Although being the most abundant cometary volatile, water is also one of the species the most difficult to tackle, because the Earth's atmosphere precludes its direct observation from the ground (except for weak lines arising from highly excited rotational or vibrational states). The 1_{10}–1_{01} fundamental line of ortho water at 556.936 GHz is expected to be among the strongest lines of the radio spectrum of comets, but its observation needs to be made

Table 3
JFCs comets with observed OH 18-cm lines (Nançay excepted)

Comet	peri. year	telescope[a)]	references
6P/d'Arrest	1976	VRO[b)]	Webber and Snyder (1977)
2P/Encke	1977	VRO[b)]	Webber et al. (1977)
		Arecibo[b)]	Bania, *personal communication* as quoted in Despois et al. (1981)
21P/Giacobini-Zinner	1985	NRAO 140'	Tacconi-Garman et al. (1990)
		DRAO	Galt (1987)
		VLA[b)]	de Pater et al. (1991)
		Parkes	Norris et al. (1985)
46P/Wirtanen	2002	Arecibo	Lovell et al. (2002)
2P/Encke	2003	Arecibo	Howell et al. (2004)
		GBT	idem
9P/Tempel 1	2005	Arecibo	Howell et al. (2007a)
		GBT	idem
		Parkes	Jones et al. (2006)
73P/Schwassmann-Wachmann 3	2006	Arecibo	Howell et al. (2007b)
		GBT	Lovell et al. (2006)

[a)] Arecibo: 300-m telescope at Arecibo, Porto Rico; DRAO: 26-m telescope, Dominion Radio Astronomical Observatory, Canada; GBT: 100-m telescope at Green Bank, USA; NRAO 140': 42-m telescope at Green Bank, USA; Parkes: 64-m telescope, Australia; VLA: array of 25-m antennas in New Mexico, USA; VRO: 36-m telescope at Vermilion River Observatory, Illinois, USA.
[b)] no detection, or doubtful detection.

Fig. 4. The OH 18-cm lines in comet 9P/Tempel 1 observed with the Green Bank radio telescope just after the impact. Note the S shape of the line, due to the Greenstein effect (asymmetric excitation caused by differential velocities within the coma). From Howell et al. (2007a).

from space. The first opportunities to observe this line in comets were provided by the Submillimeter Wave Astronomy Satellite (SWAS) (Neufeld et al., 2000) and the Odin satellite (Lecacheux et al., 2003; Biver et al., 2007b). This line is optically thick: its analysis in order to retrieve column densities and water production rates requires the coupled modelling of radiative transfer and molecular excitation (Bensch and Bergin, 2004; Zakharov et al., 2007).

The observations of JFCs with SWAS and Odin are listed in Table 4. Examples of the water line spectrum are shown in Fig. 5. Unfortunately, these instruments have specific visibility constraints and cannot observe at small solar elongations.

Water isotopologues, although observed in some long-period comets (HDO in C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp) from the ground; Altwegg and Bockelée-Morvan (2003); $H_2^{18}O$ in four comets with Odin), are not yet detected in JFCs, except for $H_2^{18}O$ observed in 73P/Schwassmann-Wachmann 3 by Odin (Biver et al., 2008a).

In the future, these observations will be pursued and extended with the Herschel Space Observatory (Crovisier, 2005). As part of the key programme *Water and related chemistry in the Solar System* (P.I. Paul Hartogh), several rotational lines of water and its isotopologues are to be observed in JFCs, including 103P/Hartley 2 at its next passage close to the Earth in October 2010.

The MIRO (*Microwave Instrument for the Rosetta Orbiter*) instrument (Gulkis et al., 2007), aboard the Rosetta Spacecraft of the European Space Agency, is also equipped with a radio spectrometer tuned to the 1_{10}–1_{01} lines of H_2O, $H_2^{18}O$ and $H_2^{17}O$ (as well as other submillimetric lines of CO, CH_3OH and NH_3). These lines will be observed at a close distance in 67P/Churyumov-Gerasimenko in 2014–2015.

3. The investigation of chemical composition from millimetric lines

Spectroscopy at radio wavelengths, together with infrared spectroscopy, is adequate for the investigation of cometary parent molecules (see, e.g., Bockelée-Morvan et al., 2005). The radio technique is very sensitive to trace species like HCN which have a large dipolar moment.

Table 5 lists all reported spectroscopic observations of JFCs at radio wavelengths (excepting water and OH). This table shows that only few molecules can be detected in JFCs by radio spectroscopy for standard observing con-

Table 4
JFCs observed with SWAS and/or Odin (557 GHz water line)

Comet	peri. year	satellite	references
19P/Borrelly	2001	Odin	Bockelée-Morvan et al. (2004)
29P/Schwassmann-Wachmann 1		Odin	Biver et al. (2007b)
2P/Encke	2003	SWAS Odin	Bensch and Melnick (2006) Biver et al. (2007b)
9P/Tempel 1	2005	SWAS Odin	Bensch et al. (2006) Biver et al. (2007a)
73P/Schwassmann-Wachmann 3	2006	Odin	Crovisier et al. (2006); Biver et al. (2008a)

Fig. 5. Observations of the 557 GHz water line in comets 2P/Encke and 9P/Tempel 1 with Odin. From Biver et al. (2007b).

ditions: four to ten molecules were detected in only five of them. This is to be compared to the ≈ 10 or more molecules detected in several Oort-cloud comets. For instance, in 22P/Kopff, only HCN, H_2S and CH_3OH could be detected (Biver, 1997). HCN is apparently the easiest molecule to detect, so that its lines may be used as a proxy for monitoring cometary activity. Carbon monoxide has a small dipolar moment which renders the detection of its rotational lines difficult, despite its presumably large abundance. This species could not be detected in the radio in any JFC, except 29P/Schwassmann-Wachmann 1 (Section 5.7) and 17P/Holmes. Many more molecules could be detected in 73P/Schwassmann-Wachmann 3 and 17P/Holmes which had exceptional observation conditions (Sections 5.5 and 5.6).

The diversity of comets from radio observations is discussed in Section 6 below.

4. Radio continuum measurements

There is a long history of observations of cometary radio continuum. The majority of observations made at centimetric wavelengths were unsuccessful or matter of debate; see the reviews of Snyder (1982) and Crovisier and Schloerb (1991) for early observations. Even for the productive and dusty comet C/1995 O1 (Hale-Bopp), only a very weak thermal continuum was detected at 0.9 cm wavelength, attributed to thermal emission of cm-sized particles (Altenhoff et al., 1999). To our knowledge, the only reported long-wavelength continuum observation of a JFC is that of comet 6P/d'Arrest at $\lambda = 2.8$ cm performed with the NRAO 43-m Green Bank telescope, which was negative (Gibson and Hobbs, 1981).

Several long-period comets were detected via their millimetre or submillimetre thermal radiation, e.g., comets 1P/Halley (Altenhoff et al., 1989), 109P/Swift-Tuttle (Jewitt, 1996), 23P/Brorsen-Metcalf (Jewitt and Luu, 1990), C/1996 B2 (Hyakutake) (Jewitt and Matthews, 1997; Altenhoff et al., 1999), C/1995 O1 (Hale-Bopp) (de Pater et al., 1998; Altenhoff et al., 1999; Jewitt and Matthews, 1999). These observations provided constraints on the total dust mass production rate and, to some extent, on the particle size distribution from measurements of the spectral index of the dust emission. A measure of the size of comet Hale-Bopp's nucleus was obtained from observations with the IRAM Plateau de Bure interferometer, thanks to the high angular resolution of the continuum maps which allowed to estimate the relative contributions of the dust and nucleus emissions (Altenhoff et al., 1999). Similar observations can be made with a single-dish radio telescope on an inactive, or low-activity comet. Indeed, this was achieved with the IRAM 30-m telescope on the Centaur 67P/Chiron (Altenhoff and Stumpff, 1995) thanks to its large size (84 km radius).

Only a few millimetre or submillimetre continuum observations of JFCs were reported (Table 6). Observations

Table 5
JFCs observed in spectroscopy with cm, mm or sub-mm ground-based telescopes

Comet	perihelion	telescope[a)]	molecules	references
29P/Schwassmann-Wachmann 1		JCMT	CO	Senay and Jewitt (1994)
		IRAM	CO	Crovisier et al. (1995); Gunnarsson et al. (2008)
		SEST	CO	Festou et al. (2001); Gunnarsson et al. (2002)
21P/Giacobini-Zinner	5 Sep. 1985	IRAM	(HCN)[b)]	Bockelée-Morvan et al. (1987)
		Effelsberg	(NH_3)[b)]	Bird et al. (1987)
19P/Borrelly	1 Nov. 1994	IRAM	HCN, CH_3OH, H_2CO	Bockelée-Morvan et al. (1995, 2004)
		JCMT	HCN	idem
45P/Honda-Mrkos-Pajdušáková	26 Dec. 1995	JCMT	HCN	Biver (1997); Biver et al. (2002)
22P/Kopff	2 Jul. 1996	IRAM	HCN, H_2S, CH_3OH	Biver (1997); Biver et al. (2002)
21P/Giacobini-Zinner	21 Nov. 1998	IRAM	HCN, CS, CH_3OH	Biver et al. (1999); Biver et al. (2002)
		CSO	HCN, CH_3OH	idem
		JCMT	HCN, CS, CH_3OH	idem
52P/Harrington-Abell	28 Jan. 1999	JCMT	(HCN)[b)], (CO)[b)]	Biver et al. (unpublished)
37P/Forbes	4 May 1999	CSO	(HCN)[b)]	Biver et al. (unpublished)
10P/Tempel 2	8 Sep. 1999	CSO	HCN, CH_3OH	Biver et al. (2002)
		JCMT	HCN	idem
141P/Machholz 2-A	9 Dec. 1999	CSO	(HCN)[b)]	Biver et al. (unpublished)
		JCMT	(HCN)[b)], (CO)[b)]	idem
2P/Encke	9 Sep. 2000	CSO	(HCN)[b)]	Biver et al. (unpublished)
73P/Schwassmann-Wachmann 3	27 Jan. 2001	CSO	(HCN)[b)]	Biver et al. (unpublished)
19P/Borrelly	14 Sep. 2001	IRAM	HCN, CS	Bockelée-Morvan et al. (2004)
67P/Churyumov-Gerasimenko	18 Aug. 2002	IRAM	(CO)[b)]	Bockelée-Morvan et al. (2004)
2P/Encke	29 Dec. 2003	IRAM	HCN, CH_3OH	Crovisier et al. (2005)
		CSO	HCN, CH_3OH	idem
		JCMT	HCN	Woodney et al. (2003, 2004)
9P/Tempel 1	5 Jul. 2005	IRAM	HCN, H_2S, CH_3OH	Biver et al. (2007a)
		CSO	CH_3OH	idem
		JCMT	(HCN)[b)]	Coulson et al. (2005)
		Mopra	(HCN)[b)]	Jones et al. (2006)
		ATCA	(HCN)[b)], (CH_3OH)[b)]	Jones et al. (2006)
		Medicina	(NH_3)[b)]	Tozzi et al. (2007)
73P/Schwassmann-Wachmann 3	7–8 Jun. 2006	IRAM	HCN, CS, H_2S, CH_3OH, H_2CO, CH_3CN, HNCO	Biver et al. (2006, 2008a)
		CSO	HCN, CH_3OH, H_2CO	Biver et al. (2006, 2008a); Lis et al. (2008)
		APEX	HCN, CS, CH_3OH	Biver et al. (2006, 2008a)
		Kitt Peak	HCN	Milam et al. (2006)
		SMT	HCN	Drahus et al. (2007a)
17P/Holmes	4 May 2007	IRAM	HCN, CO, CS, CH_3OH, HNC, H_2CO, CH_3CN, H_2S, SO	Biver et al. (2008b); Bockelée-Morvan et al. (2008)
		IRAM PdB	HCN, HNC, HC_3N, HCO^+	Boissier et al. (2008)
		CSO	HCN, CO, CS, CH_3OH, HNC, H_2CO	Biver et al. (2008b)
		Kitt Peak	HCN, CS, H_2S, CH_3OH, H_2CO	Drahus et al. (2007b, 2008b)
		SMT	HCN	Drahus et al. (2008a)
46P/Wirtanen	2 Feb. 2008	IRAM	HCN	Biver et al. (unpublished)

[a)] APEX: Atacama Pathfinder Experiment (15-m telescope), Chile; ATCA: Australia Telescope Compact Array; CSO: Caltech Submillimeter Observatory 10-m telescope at Mauna Kea, Hawaii, USA; Effelsberg: MPIFR 100-m telescope at Effelsberg, Germany; IRAM: Institut de radio astronomie millimétrique 30-m telescope at Pico Veletta, Spain; IRAM PdB: IRAM interferometer at Plateau de Bure, France; JCMT: James Clerk Maxwell Telescope (15 m) at Mauna Kea, Hawaii, USA; Kitt Peak: 12-m telescope at Kitt Peak, Arizona, USA; Medicina: 32-m telescope, Bologna, Italy; Mopra: 22-m telescope, Australia; SEST: Swedish-ESO Submillimetre Telescope (15 m) at La Silla, Chile; SMT: Sub-Millimeter Telescope (10 m) at Mt Graham, Arizona, USA.
[b)] no detection.

Table 6
JFCs observed in radio continuum (only 17P/Holmes was detected)

Comet	perihelion	telescope[a)]	frequency [GHz]	references
6P/d'Arrest	12 Aug. 1976	NRAO 140'	11	Gibson and Hobbs (1981)
21P/Giacobini-Zinner	5 Sep. 1985	Effelsberg	24	Altenhoff et al. (1986)
4P/Faye	16 Nov. 1991	JCMT	375	Jewitt and Luu (1992)
67P/Churyumov-Gerasimenko	18 Aug. 2002	IRAM	250	Bockelée-Morvan et al. (2004)
17P/Holmes	4 May 2007	IRAM PdB	90	Boissier et al. (2008)
		IRAM	250	Altenhoff (personal communication)
		SMA		Qi (personal communication)

[a)] See notes to Tables 3 and 5; SMA: Submillimeter Array, Hawaii, USA.

of 21P/Giacobini-Zinner (Altenhoff et al., 1986), 4P/Faye (Jewitt and Luu, 1992) and 67P/Churyumov-Gerasimenko (Bockelée-Morvan et al., 2004) were not conclusive, a result not surprising given their low activity level. Note that 67P was observed as it was at 3 AU from the Sun in order to support Rosetta science operations, following studies of its dust tail which suggested an unexpected high mass loss rate of large grains (Fulle et al., 2004).

Typically, a comet should have a *figure of merit* (cf. Table 1) larger than ≈ 7 to be detected at 250 GHz, on the basis of a rms noise of 1 mJy, achievable in three hours of winter observations with the IRAM 30-m telescope. Other existing major (sub)millimetric telescopes have similar performances.

Recently, the huge outburst that comet 17P/Holmes underwent on 24 October 2007 allowed the first successful radio continuum observations of a JFC (Section 5.6).

Fig. 6. The OH and H_2O production rates of 2P/Encke, measured at Nançay (OH) and with Odin (H_2O) for different returns, as a function of heliocentric distance (left is pre-perihelion and right is post-perihelion). From Crovisier et al. (2002, and in preparation) and Biver et al. (2007b).

5. Discussion of specific comets

5.1. *2P/Encke*

2P/Encke is the shortest-period comet, famous for its non-gravitational forces and its seasonal effects. Observations of OH in this comet are not easy, because the water production rate is important only close to perihelion (at a distance $q = 0.338$ AU from the Sun), when the OH lifetime is short. The preliminary report of a detection of OH by Webber et al. (1977) at the 1977 passage, must be considered as dubious. Only marginal detections were obtained at Nançay in 1980 and 1994 (Bockelée-Morvan et al., 1981; Crovisier et al., 2002). Confirmed detections of OH were made at the 2003 and 2007 passages (Howell et al., 2004, Crovisier et al., in preparation).

Fig. 5 shows the water spectrum observed by Odin in 2P/Encke. Fig. 6 shows the OH and water production rates measured for different passages of 2P/Encke. HCN and CH_3OH could be detected at the 2003 passage. The methanol abundance is observed to be relatively high: about 4% relative to water.

5.2. *21P/Giacobini-Zinner*

21P/Giacobini-Zinner is the archetype of carbon chain-depleted comets (see Section 6). It was observed at its 1998 passage as part of a multi-wavelength campaign. Only HCN, CS and CH_3OH were then detected (Biver et al., 1999). A methanol abundance $[CH_3OH]/[H_2O] = 1.5\%$ was observed, which is amongst the lowest abundances observed in comets for this specie (Biver et al., 2002). This depletion is confirmed by infrared observations and is also observed for other volatiles (Weaver et al., 1999; Mumma et al., 2000).

5.3. *19P/Borrelly*

This comet was observed at its 1994 passage and in the frame of a multi-wavelength campaign in support to the flyby of the comet on 22 Sept. 2001 by *Deep Space 1* (Soderblom et al., 2002).

$Q_{\rm OH}$ was $\approx 2.5\times10^{28}$ s^{-1} at $r_h \approx 1.4$ AU at both returns. Odin observed $Q_{\rm H_2O} = 3.8\pm0.5\times10^{28}$ s^{-1} at the time of the flyby ($r_h = 1.36$ AU). Only HCN and CS could be detected at IRAM in 2001, whereas CH_3OH and H_2CO were detected at the 1994 passage (Bockelée-Morvan et al., 2004). The HCN and OH lines were asymmetric and blueshifted, showing asymmetric outgassing towards the Sun.

5.4. *9P/Tempel 1*

The *Deep Impact* mission flew by comet 9P/Tempel 1 on 4 July 2005. An impactor was sent to hit the nucleus at 10.2 km s^{-1} to excavate pristine material from the sub-surface (A'Hearn et al., 2005). A multi-wavelength campaign was organised in support to this mission (Meech et al., 2005).

In March–April 2005, $Q_{\rm OH} \approx 4\times10^{27}$ s^{-1} was measured at Nançay when the comet was at $r_h \approx 1.76$ AU (Fig. 3; Biver et al., 2007a). The OH lines were also observed in April–June with the Arecibo telescope (Howell et al., 2007a). Around the time of the impact ($r_h = 1.51$ AU), $Q_{\rm H_2O}$ was $\approx 10^{28}$ s^{-1} from the observations of SWAS (Bensch et al., 2006) and Odin (Fig. 5; Biver et al., 2007a). The OH observations were difficult at that time because of the small inversion of the OH maser, but the 18 cm lines could nevertheless be detected with the Green Bank telescope (Fig. 4; Howell et al., 2007a) and possibly with the Parkes telescope (Jones et al., 2006). The evolution of the OH and H_2O production rates as measured from all radio observations is plotted in Fig. 7. The water lines were also searched for — but not detected —around the time of impact by the MIRO radio spectrometer aboard Rosetta. Although MIRO could detect the 557 GHz water line of C/2002 T7 (LINEAR) (Gulkis et al., 2007), the 30-cm telescope of this instrument is only suited for close up observations.

Only HCN, CH_3OH and H_2S could be detected from other radio spectroscopic observations (Table 5; Biver et al., 2007a). These species show abundances of 0.12, 2.7 and 0.5% relative to water, respectively, which are comparable to the mean values observed in many comets. The variation of the HCN signal intensity was found to be consistent with the 1.7-day rotation period of the nucleus. Post-impact observations did not reveal any significant change of the outgassing rates or of the relative abundances (except for a possible increase of the CH_3OH outgassing).

5.5. *73P/Schwassmann-Wachmann 3*

The hydroxyl radical was monitored in 73P/Schwassmann-Wachmann 3 at Nançay at its last three passages (Crovisier et al., 1996; Colom et al., 2006). In 1995, an unexpected outburst of the OH production was observed, followed by an increase of the visual brightness. Then, images showed that the comet had split. Since that time, the comet continuously experienced fragmentation (Sekanina, 2005). The 2006 passage was especially spectacular, as the comet made a close approach to Earth at only 0.08 AU in mid-May, just before its perihelion on 6 June. The two main fragments, B and C, then both showed water production rates $\approx 2\times10^{28}$ s^{-1} (Fig. 8). They could be the targets of detailed spectroscopic observations with several radio telescopes (Tables 3, 4, 5; Biver et al., 2006, 2008a; Villanueva et al., 2006; Drahus et al., 2007a; Lis et al., 2008).

The HCN, CH_3CN, HNCO, CH_3OH, H_2CO, H_2S and CS molecules were detected in addition to OH and H_2O. Except for HCN, both fragments show depletion in volatiles with respect to water, compared to other comets. The two fragments B and C were seen to have remarkably similar compositions, suggesting that the original nucleus of the comet had a homogeneous composition. Similar conclusions were drawn from infrared spectroscopic observations (Dello Russo et al., 2007; DiSanti et al., 2007; Kobayashi et al., 2007).

A deep search for hydrogen isocyanide (HNC) was conducted at the CSO in fragment B (Lis et al., 2008). HNC has been observed in a dozen bright comets with ratios [HNC]/[HCN] ranging from 2 to 15% and systematically increasing when the heliocentric distance decreases. In 73P(B), a low upper limit [HNC]/[HCN] $\leq 1.1\%$ was found, which is about 7 times lower than the value found in moderately active comets at similar heliocentric distances. This puts new constraints on the still unresolved question of the origin of HNC in comets, and on the evolution of the [HNC]/[HCN] ratio with heliocentric distance.

5.6. *17P/Holmes*

The unexpected outburst of 17P/Holmes on 24 October 2007 (Green, 2007; Bockelée-Morvan, 2008a) made it temporarily one of the brightest JFCs (Table 1). Although water could not be observed at the onset of the outburst, and although it is difficult to define and compare production rates for such a variable event, the peak $Q_{\rm H_2O}$ possibly exceeded 10^{30} s^{-1} (Dello Russo et al., 2008). Many observations could be scheduled on short notice. However, at the time of writing, most of the results are not yet published and it is premature to present a comprehensive review of this exceptional event.

Fig. 9. The OH spectra of comet 17P/Holmes observed at Nançay just after its outburst on October 24.2. From Crovisier et al. (2008).

Observations could be scheduled at Nançay immediately and the comet was monitored until 9 November. The comet

Fig. 7. The OH and H_2O production rates measured in 9P/Tempel 1 from observations at Nançay, Arecibo, Green Bank and with SWAS and Odin. The OH production rates were derived using the OH inversion model of Despois et al. (1981); they have been multiplied by 1.1 to account for the water photodissociation yield. From Biver et al. (2007a); Howell et al. (2007a); Bensch et al. (2006).

Fig. 8. Evolutions of the production rates of components B and C of comet 73P/Schwassmann-Wachmann 3, from the OH lines observed at Nançay. From Colom et al. (2006).

Fig. 10. The continuum map of 17P/Holmes observed at 90 GHz with the IRAM interferometer at Plateau de Bure on 27 and 28 October 2007. From Boissier et al. (2008).

was detected initially with a signal increasing (Fig. 9); this was followed by a levelling-off and then a decline in the signal strength. The line was observed in emission whereas the OH inversion was expected to be zero or slightly negative. Thus the signal was due to thermal emission in a quenched coma. These observations are to be compared with the monitoring of the HCN lines made at IRAM, CSO, Kitt Peak and SMT (Biver et al., 2008b; Drahus et al., 2007b, 2008a).

Soon after the outburst of 17P/Holmes, the intensities of the millimetre molecular lines were comparable to those recorded in comet Hale-Bopp. It was thus possible to search for weak signatures of rare isotopes. The $HC^{15}N$ and $H^{13}CN$ $J(3–2)$ lines (near 258–259 GHz) were detected at the IRAM 30-m telescope. Isotopic ratios $^{14}N/^{15}N = 139 \pm 26$ and $^{12}C/^{13}C = 114 \pm 26$ were derived for HCN, to be compared to the Earth values of 272 and 89, respectively (Bockelée-Morvan et al., 2008). This $^{14}N/^{15}N$ value in HCN is comparable to that measured in CN for a dozen comets of different dynamical families, including 17P/Holmes (e.g., Jehin et al., 2004; Manfroid et al., 2005; Bockelée-Morvan et al., 2008). The same conclusion is obtained for comet Hale-Bopp after a reanalysis of previous published measurements of $^{14}N/^{15}N$ in HCN (Jewitt et al., 1997; Ziurys et al., 1999; Arpigny et al., 2003; Bockelée-Morvan et al., 2008). There is some debate on the origin of CN in cometary atmospheres (Fray et al., 2005): a similar isotopic composition in HCN and CN is compatible with HCN being the prime parent of CN. These results also suggest that JFCs and Oort cloud comets present a similar anomalous nitrogen isotopic composition in HCN. Important isotopic fractionation of nitrogen should have taken place at some stage of the Solar System formation under a mechanism which is still not understood.

Continuum observations were initiated from the millimetre to submillimetre domains, with the objective to constrain the properties of the dust cloud that expanded with time. Continuum maps at $\lambda = 3$ mm were obtained at the IRAM Plateau de Bure interferometer two days after the outburst (Fig. 10; Boissier et al., 2008). Observations with the IRAM 30-m telescope (Altenhoff, personal communication) and with the Submillimeter Array (Qi, personal communication) were conducted as well.

5.7. *29P/Schwassmann-Wachmann 1, distant comets and Centaurs*

At distances $r_h \gtrsim 4$ AU, the nucleus surface equilibrium temperature is too low to allow a significant sublimation of water ice. Another mechanism has to be responsible for cometary activity at large distances from the Sun. Indeed, the activity of 29P/Schwassmann-Wachmann 1 at $r_h \approx 6$ AU was found to be governed by the sublimation of carbon monoxide. This was first observed from the radio detection of the $J(2–1)$ line of CO at the JCMT by Senay and Jewitt (1994). The observations of radio lines of CO in comets are not easy: the rotational lines of this molecule, which has a small dipolar moment, are weak. On the other hand, infrared and ultraviolet emissions of CO, driven by fluorescence excited by the Sun, are expected to be even more difficult to observe in distant comets.

29P/Schwassmann-Wachmann 1 is an atypical comet in a nearly circular orbit with $a = 6.06$ AU, classified either as a JFC or as a Centaur. Subsequent studies of CO in this comet were made by Crovisier et al. (1995), Festou et al. (2001), Gunnarsson et al. (2002, 2008) and Gunnarsson (2003). Fig. 11 shows a representative spectrum of CO in 29P/Schwassmann-Wachmann 1. The line is strongly asymmetric with a very narrow component at negative velocities. The width of the narrow feature (0.14 km s^{-1}) corresponds to a kinetic temperature < 12 K, which puts stringent constraints on the physical conditions in the coma.

The inferred CO outgassing is $Q_{CO} \approx 4 \times 10^{28}$ s^{-1}. A deep integration on the 557 GHz line of water with Odin in June 2003 yielded a tentative detection (corresponding

Fig. 11. The $J(2–1)$ line of CO observed in comet 29P/Schwassmann-Wachmann 1 at 6.1 AU from the Sun with the IRAM 30-m telescope. From Crovisier et al. (1995).

to $Q_{H_2O} \lesssim 2.5 \times 10^{28}$ s^{-1}) during the first part of the observation, which could not be confirmed later (Biver et al., 2007b).

Searches for an extended source of CO (coming from, e.g., the sublimation of icy grains) were undertaken by mapping the CO $J(2–1)$ line. Observations at SEST first suggested such an extended source (Festou et al., 2001), but were not confirmed by subsequent observations at IRAM (Gunnarsson et al., 2008).

This discovery of carbon monoxide in a distant comet prompted a search for the same species in Centaurs. A detection of CO in 95P/Chiron was claimed by Womack and Stern (1995, 1999). However, it was not confirmed either in Chiron or in other Centaurs (Rauer et al., 1997; Bockelée-Morvan et al., 2001b; Jewitt et al., 2008).

The long-period comet C/1995 O1 (Hale-Bopp) was observed by radio spectroscopy up to $r_h = 14$ AU, allowing us to study the evolution of the sublimation of water, CO and various other molecules as a function of heliocentric distance (Biver et al., 2002). 29P/Schwassmann-Wachmann 1 and C/1995 O1 (Hale-Bopp) are still the most distant comets in which molecular lines could be detected in the radio.

5.8. *D1993/F2 Shoemaker-Levy 9 and its collision with Jupiter*

To be comprehensive, the case for D1993/F2 Shoemaker-Levy 9 (hereafter SL9) should be discussed. SL9 was discovered in late March 1993 after a first encounter with Jupiter on 7 July 1992 which broke it in multiple fragments and triggered activity. The fragments collided with Jupiter on 16–22 July 1994. Whether SL9 was a bona fide JFC or an asteroid has been the subject of debates (Noll et al., 1996). Indeed, whereas each fragment appeared to be surrounded by a dust coma, no sign of gas species could be detected before the impacts. Searches for CO at radio wavelengths at CSO, SEST and IRAM were negative (M. Festou, D. Jewitt, E. Lellouch, H. Rickman, M. Senay, *personal communications* as quoted in Crovisier, 1996), as was the case for other searches for gas in the visible. The post-impact observations revealed radio lines of CO, HCN, CS, OCS, possibly H_2O (Crovisier, 1996). Some of these lines persisted for months or even years, as revealed by the monitoring of the CO, CS and HCN lines with the JCMT and IRAM 30-m telescopes (Moreno et al., 2003). However, these molecules are not likely to be remnants from the comet. They were rather resulting from shock chemistry in the planet's atmosphere. Their investigation pertains to the physics and chemistry of Jupiter's atmosphere rather than to cometary physics (Lellouch, 1996).

6. Comparison with other cometary families

Although the sample is still sparse, there is no obvious correlation between the dynamical class and the chemical composition of comets (Biver et al., 2002; Crovisier, 2007). This is shown for the relative abundances of HCN and CH_3OH in Fig. 12.

A taxonomy from narrow-band spectrophotometry in the visible (A'Hearn et al., 1995) or from CCD spectroscopy (Fink, 2006) has been proposed: *typical* comets and *carbon chain-depleted* comets are distinguished according to the C_2/CN ratio. Whereas typical comets are present in all dynamical classes, carbon chain-depleted comets are almost exclusively restricted to JFCs. Among JFCs well-observed by radio spectroscopy, 2P/Encke, 9P/Tempel 1 and 22P/Kopff are typical, 19P/Borrelly, 21P/Giacobini-Zinner and 73P/Schwassmann-Wachmann 3 are carbon chain-depleted. These three comets are also depleted in methanol (with $[CH_3OH]/[H_2O] = 1.7$, 1.5 and 0.9%, respectively, to be compared to 4, 2.7 and 2.5%, respectively, for the three typical comets). Among the rare non-JFCs which are carbon chain-depleted, C/1999 S4 (LINEAR) also showed a very low methanol abundance ($[CH_3OH]/[H_2O] \leq 1\%$; Bockelée-Morvan et al., 2001a).

The point of view from infrared observations is discussed by DiSanti and Mumma (2008). The sample is still meager, including 9 comets with only 2 JFCs. As for the radio sample, although there are important comet-to-comet variations of composition, no obvious difference is found among the various dynamical classes of comets.

7. Conclusion: Prospects for future observations

Radio observations of JFCs (see Table 7 for a summary) are still sparse. Up to now, successful radio observations of JFCs have been limited to a dozen objects, mainly restricted to exceptional comets (comets which made a close approach to Earth and/or which showed an outburst), or to the targets of space missions for which a special effort was made.

Fig. 12. The HCN and methanol abundances relative to water for a set of comets observed by radio spectroscopy. The sizes of the ellipses represent the errors of the measurements. Note that the spread for methanol abundances is much larger than for HCN. There is no obvious difference between JFCs (in green in the electronic version) and the other comets. Adapted from Crovisier et al. (2007).

New radio instruments are to be soon available for the observations of comets with an increased sensitivity:

- the Large Millimeter Telescope (LMT), under completion in Mexico (Irvine and Schloerb, 2005); with its 50-m antenna, it will be soon the largest millimetric telescope of its category;
- the Herschel Space Observatory, to be launched in 2009 (Crovisier, 2005);
- the Atacama Large Millimetre Array (ALMA) in Chili (Biver, 2005; Bockelée-Morvan, 2008b);
- the Square Kilometre Array (SKA), which will operate at decimetric-centimetric wavelengths (Butler et al., 2004);
- the MIRO instrument on Rosetta, a 30-cm diameter radio telescope to observe dedicated molecular radio lines in situ in comet 67P/Churyumov-Gerasimenko, as well as the continuum emission of its nucleus (Gulkis et al., 2007).

Specific opportunities to observe JFCs with a high FM will occur in the near future (Table 1):

- 103P/Hartley 2 in October 2010 (with a flyby of the redirected Deep Impact spacecraft, renamed as the EPOXI mission);
- 45P/Honda-Mrkos-Pajdušáková in August 2011.

It will thus be possible to significantly increase the sample of JFCs with known molecular composition, and to pursue the comparative study of the different cometary families.

Isotopic measurements in cometary volatiles are also important diagnostics on the origin of cometary material. Most measurements have been made using millimetre or submillimetre spectroscopy. However, if one excepts the Jupiter-family comet 17P/Holmes (Section 5.6), the capabilities of ground and space-based instrumentation have limited the investigations to a few bright long-period comets, as reviewed in Altwegg and Bockelée-Morvan (2003) and Bockelée-Morvan et al. (2005) and reported in Biver et al. (2007b). Isotopic ratios could be different in JFCs and Oort cloud comets if the two populations formed at different places or different times in the solar nebula. Though the LMT promises to be very useful for the study of the molecular composition of JFCs, isotopic investigations with this telescope will be limited to exceptionally bright comets (Irvine and Schloerb, 2002). The HIFI instrument of the Herschel Space Observatory is to provide the oppor-

Table 7
Summary of radio observations of JFCs

Comet	FM	OH	H_2O	HCN	CH_3OH	other molecules	continuum
2P/Encke	2	X	X	X	X		
4P/Faye	1.3	X					
6P/d'Arrest	1	M					
9P/Tempel 1	1.3	X	X	X	X	H_2S	
10P/Tempel 2				X	X		
17P/Holmes	> 60	X		X	X	several	X
19P/Borrelly	2	X	X	X	X	several	
21P/Giacobini-Zinner	3	X		X	X	CS	
22P/Kopff	4	X		X	X	H_2S	
24P/Schaumasse	2	X					
29P/Schwassmann-Wachmann 1	< 0.4		M			CO	
45P/Honda-Mrkos-Pajdušáková	2	M		X			
46P/Wirtanen	0.7	X		X			
67P/Churyumov-Gerasimenko	0.6	M					
73P/Schwassmann-Wachmann 3	25	X	X	X	X	several	
81P/Wild 2	1	M					
141P/Machholz 2	2	M					

FM: figure of merit for best passage (see Table 1);
X: secure detection; M: marginal detection.

tunity to detect the 1_{10}–1_{01} line of HDO at 509.3 GHz in comet 103P/Hartley 2, and to observe simultaneously several H_2O lines for an accurate determination of the D/H ratio in water. ALMA will allow the detection of HDO at 465 and 894 GHz in short-period comets with $FM > 5$, and DCN in comets with $FM > 10$.

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