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Observations of water in comets with Odin*

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Abstract. The Odin satellite, which can observe the 1_{10}–1_{01} rotational line at 557 GHz of ortho water with a high spectral resolution (80 m s^{-1}) and a spatial resolution of 2.1′, is well suited for cometary studies. The intensity of this line provides an estimate of the water production rate. The line width gives a direct measure of the coma expansion velocity. The line centre position and shape are affected by the anisotropy of the outgassing and by optical depth effects. Comets observed with Odin up to now are C/2001 A2 (LINEAR) during the commissioning phase of the satellite, 19P/Borrelly at the time of the Deep Space 1 flyby, C/2000 WM_1 (LINEAR), and 153P/2002 C1 (Ikeya-Zhang). For this last comet, thorough observations were made at the moment of its closest approach to Earth at the end of April 2002. A deep integration resulted in the detection of the 1_{10}–1_{01} line of $H_2^{18}O$ at 548 GHz. No $^{16}O/^{18}O$ isotopic anomaly is found.

Key words. comets: general – comets: individual: C/2001 A2 (LINEAR), 19P/Borrelly, C/2000 WM_1 (LINEAR), 153P/2002 C1 (Ikeya-Zhang) – radio lines: solar system – submillimeter

1. Introduction

Water is the main constituent of the ices of cometary nuclei. The study of cometary water is thus crucial for cometary science. The knowledge of water production rates is a requisite for the determination of the relative abundances of cometary volatiles. Close to the Sun, the sublimation of water is the driver of cometary activity. The measurement of the water production rate and of its time evolution thus provides a quantitative evaluation of cometary activity.

Ironically, although being the most abundant cometary volatile, water is also one of the species the most difficult to observe. The opacity of the Earth's atmosphere precludes its observation from the ground, except for weak lines arising from highly excited rotational or vibrational states. Most of the time, observers have to rely on secondary indicators, such as the photodissociation products of water (H, O, OH), in order to estimate water production rates in comets.

The first direct detections of cometary water were from the infrared vibrational bands observed in comet 1P/Halley at high-altitude with the *Kuiper Airborne Observatory* and in situ observations with the *VEGA–1* space probe. Rotational lines of water (the 2_{12}–1_{01} and 3_{03}–2_{12} lines close to 180 μm) were first observed by the *Infrared Space Observatory* in comet

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** Deceased

Table 1. The four comets observed with Odin

comet	dates of observation	r_h [AU]	Δ [AU]	Q[H_2O] [10^{28} molec. s^{-1}]	remarks
C/2001 A2 (LINEAR)	2001/04/27	0.94	0.83		first observation
	2001/06/20–07/07	0.93–1.13	0.24–0.28	5–8	
19P/Borrelly	2001/09/22–24	1.36	1.47	3.3 ± 0.6	*Deep Space 1* flyby
	2001/11/05	1.48	1.34	2.3 ± 0.4	
C/2000 WM_1 (LINEAR)	2001/12/07	1.13	0.33	4.2 ± 0.9	
	2002/03/12	1.16	1.24	6.7 ± 0.5	
153P/2002 C1 (Ikeya-Zhang)	2002/04/22	0.92	0.42	25.8 ± 1.1	
	2002/04/24–28	0.95–1.02	0.41	17.7 ± 1.4	

r_h and Δ are the distances of the comet to Sun and Earth, respectively, and Q[H_2O] is the water production rate

C/1995 O1 (Hale-Bopp) (Crovisier et al. 1997). The 1_{10}–1_{01} fundamental line of ortho H_2O (at 556.936 GHz) is expected to be the strongest line of the radio spectrum of comets (Bockelée-Morvan 1987). This line was first observed by heterodyne techniques with the *Submillimeter Wave Astronomy Satellite* in comet C/1999 H1 (Lee) (Neufeld et al. 2000; Chiu et al. 2001).

The possibility to observe cometary water lines with heterodyne techniques, with high sensitivity and a high spectral resolution, opens new insights for cometary science. We present here a preliminary report of high-resolution heterodyne observations of the 557 GHz line with the Odin satellite in four comets.

2. Observations

The characteristics of the Odin satellite and its operation are described in detail in Frisk et al. (2003) and Olberg et al. (2003). They are briefly summarized below.

The Odin antenna, with an equivalent diameter of 1.1 m, provides a spatial resolution of 2.1′ at 557 GHz with a beam efficiency of 0.9. Odin is equipped with four receivers tunable in the frequency range 486–580 GHz. They are based on Schottky mixers cooled to 140 K and have system temperatures $\approx$ 3000 K (SSB). The 557 GHz $H_2^{16}O$ line, or the 548 GHz $H_2^{18}O$ line, can be observed with two of these receivers simultaneously.

The backend consists of three spectrometers: one acousto-optical spectrometer (AOS) of 1.05 GHz bandwidth and 1.0 MHz resolution, and two splittable autocorrelation spectrometers which, in their high-resolution mode, provide a total bandwidth of 100 MHz and 140 kHz resolution. This resolution corresponds to 80 m s^{-1} at 557 GHz, which is particularly adequate for the study of narrow cometary lines (≈ 1.5 km s^{-1} wide).

The rms noise typically achieved in one orbit ($\approx$ 1 hour of integration) is $\int T_{\rm mB} dv = 0.14$ K km s^{-1} over the width of a cometary line. This sensitivity allows us to detect at the 5–σ level a comet with $Q[H_2O] = 10^{28}$ molec. s^{-1} at 1 AU from the Sun and from the Earth. It should be noted that Odin can only observe comets when they are at a solar elongation between 60° and 120°.

The cometary observations made with Odin are summarized in Table 1. All these observations were coordinated with other molecular radio observations performed at the *Institut de Radioastronomie Millimétrique* (*IRAM*) and/or the *Caltech Submillimeter Observatory* (*CSO*) (Biver et al. 2002; Bockelée-Morvan et al. 2003) and with observations of the OH radical performed at 18 cm wavelength at the Nançay radio telescope (Crovisier et al. 2002).

2.1. C/2001 A2 (LINEAR)

Comet C/2001 A2 (LINEAR) was observed during the commissioning phase of Odin, as soon as 27 April 2001. These observations were indeed the first astronomical results of the satellite (Lecacheux 2001). The signal was strong enough (4 to 14 K km s^{-1} at peak position; Fig. 1) that the comet could be used to check the pointing of the telescope. The comet showed several outbursts of activity, possibly associated with nucleus split up. It passed at only 0.24 AU from the Earth at the end of June and further observations with detailed mapping were carried out.

2.2. 19P/Borrelly

The short-period comet 19P/Borrelly was observed with Odin at the moment of the *Deep Space 1* flyby (Fig. 2) on 22–24 September 2001 and on 5 November 2001. A detailed account of the observation, grouped with other molecular microwave observations, is given by Bockelée-Morvan et al. (2003).

2.3. C/2000 WM_1 (LINEAR)

Comet C/2000 WM_1 (LINEAR) was observed and mapped by Odin on 7 December 2001, when it was at only 0.33 AU from the Earth (Fig. 3). The observation was repeated on 12 March 2002.

2.4. 153P/2002 C1 (Ikeya-Zhang)

Comet 153P/2002 C1 (Ikeya-Zhang) was a great opportunity for cometary observations in Spring 2002. The comet reached $Q[H_2O] \gtrsim 5 \times 10^{29}$ s^{-1} when close to its perihelion on 18 March 2002 (Dello Russo et al. 2002) and passed at only 0.40 AU from the Earth at the end of April. Extensive observations of this comet were scheduled. They included a mapping of the 557 GHz line (Fig. 4), and a deep integration (45 hours) to search for the 1_{10}–1_{01} line at 547.676 GHz of

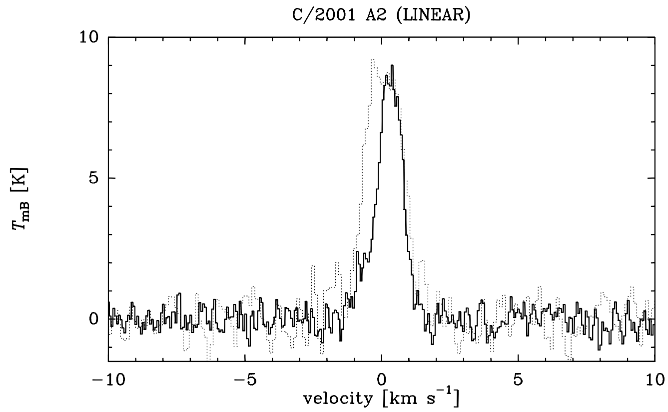

Fig. 1. The 1_{10}–1_{01} H_2O line at 557 GHz observed by Odin in comet C/2001 A2 (LINEAR) on 2.2 July 2001 (full line). For comparison, the J(3–2) line of HCN observed at the *CSO* is also shown (scale expanded by $\times 10$, dotted line). The difference between the profiles is due to self-absorption in the water line.

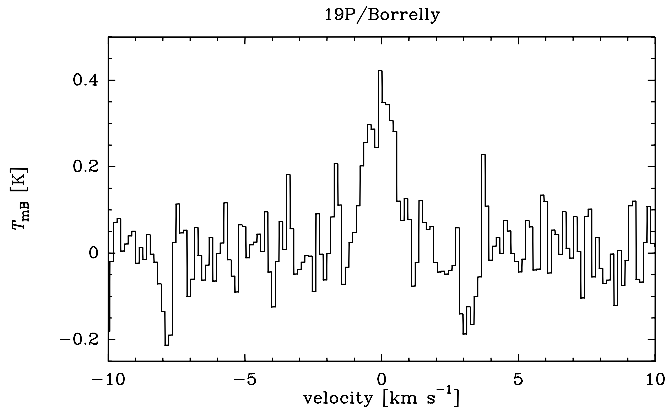

Fig. 2. The 1_{10}–1_{01} H_2O line at 557 GHz observed by Odin in comet 19P/Borrelly on 22.2–24.4 September 2001, at the time of the *Deep Space 1* flyby.

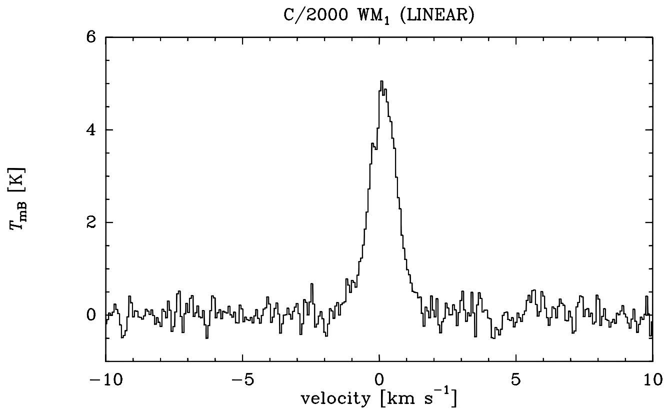

Fig. 3. The 1_{10}–1_{01} H_2O line at 557 GHz observed by Odin in comet C/2000 WM$_1$ (LINEAR) on 7.9 December 2001.

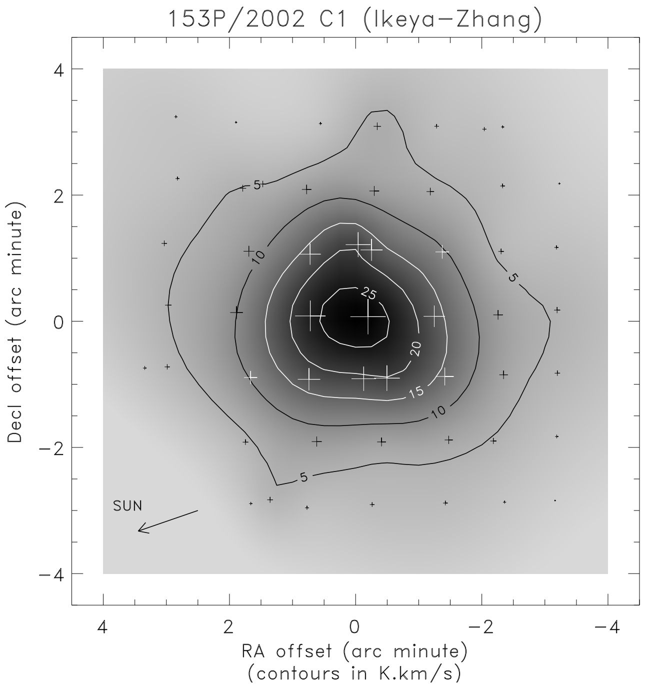

Fig. 4. The grey-scale and contours show the line area map of the 557 GHz water line observed with the Odin AOS in comet 153P/2002 C1 (Ikeya-Zhang) on 22 April 2002, when at 0.42 AU from the Earth. Crosses are plotted at the sampled points, with sizes proportional to the line areas. The direction of the Sun is given by an arrow.

the $H_2^{18}O$ isotopic variety of water, which was detected with $\int T_{\rm mB} dv = 0.23 \pm 0.02$ K km s^{-1} (Fig. 5) (Lecacheux & Biver 2002).

3. Discussion

A model has been developed to predict the emission of infrared and radio water lines in comets (Bockelée-Morvan 1987; Chiu et al. 2001). It includes radiative excitation of the vibrational bands by the solar radiation field as well as collisional excitation. The coma is assumed to be in spherical expansion with a velocity (typically 0.8 km s^{-1}) evaluated from molecular radio line shapes. The temperature of the cometary atmosphere (typically 60 K) is estimated from the relative intensities of the rotational lines of molecules such as methanol observed at *IRAM* or *CSO*. Radiative transfer effects in the excitation are treated by an escape probability method. This model has been updated to consider collisional excitation by electrons, following Biver (1997). In this formulation, the electronic density is taken from the past observations of 1P/Halley, with a scaling factor. This scaling factor has been tailored so that the evolution of the water line vs the nucleus distance observed in the maps could be reproduced. The line shapes and intensities are evaluated by numerical integration using a radiative transfer code. We have assumed an ortho-to-para ratio of 3 for cometary water[1].

Thanks to the good velocity resolution of Odin, the shapes of the 557 GHz lines are accurately known. For comets C/2001 A2 and 153P/2002 C1, which were observed with a high signal-to-noise ratio, the lines are asymmetric with redshifted centroids. No such asymmetry is found for the HCN J(3–2) or $H_2^{18}O$ 1_{10}–1_{01} lines observed in the same comets (Figs 1 and 5). We attribute this asymmetry to an optical depth effect: wa-

[1] Using the ortho-to-para ratios effectively measured in some comets ($\approx$ 2.4; e.g., Crovisier et al. 1997) would not affect significantly Q[H_2O].

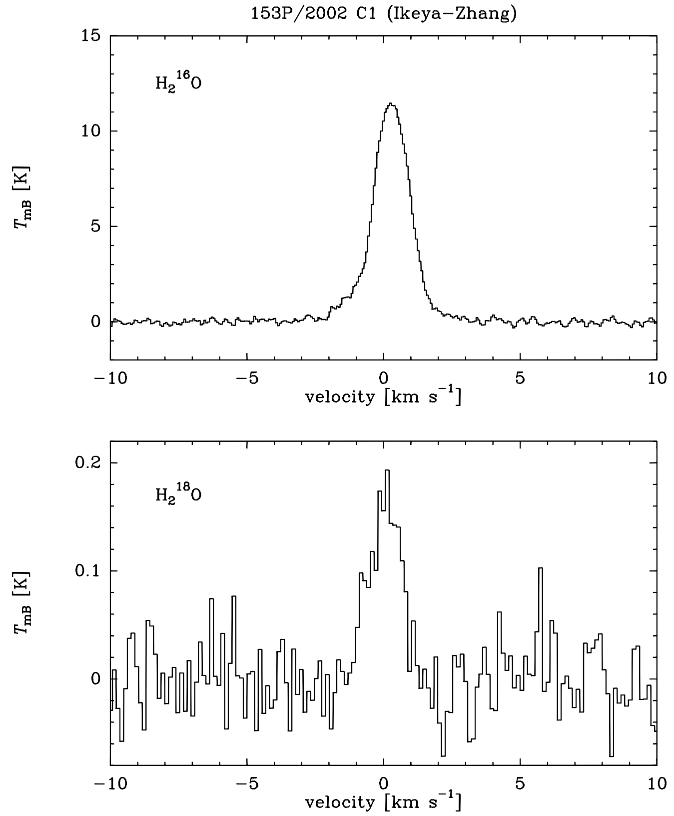

Fig. 5. The 1_{10}–1_{01} lines of $H_2^{16}O$ (top) and $H_2^{18}O$ (bottom) observed in comet 153P/2002 C1 (Ikeya-Zhang) on 24–28 April 2002 by Odin.

ter is rotationally relaxed in the outer coma, so that molecules in the foreground (which have negative radial velocities since the coma atmosphere is in expansion) absorb the 1_{10}–1_{01} line emission of the central region. This results in a depletion of the blueshifted side of the line. Our water emission model fully reproduces this effect. A velocity offset of the molecular lines is also expected from the anisotropic sublimation of cometary nucleus ices. But for the highly saturated 557 GHz water line, the line shape is entirely dominated by optical depth effects.

The water production rates derived with our model are reported in Table 1. They compare well with production rates obtained by other means (e.g., Bockelée-Morvan et al. 2003, Dello Russo et al. 2002). A discussion of the water production rates and of the constraints of the Odin observations on water excitation will be deferred to a future paper.

The same model has been used to interpret the $H_2^{18}O$ line observed in 153P/2002 C1. A production rate $Q[H_2^{18}O] = 4.0 \pm 0.3 \times 10^{26}$ s^{-1} is found. Comparing with the simultaneous $H_2^{16}O$ line observations, we deduce an isotopic ratio $^{16}O/^{18}O = 450 \pm 50$ (the error given here is just that resulting from the uncertainties in the line areas and does not include the uncertainty due to excitation modelling). This ratio is compatible with the terrestrial ratio (499 according to Anders & Grevesse 1989). A similar ratio was observed for the H_3O^+ ion in 1P/Halley from in situ mass spectrometry aboard *Giotto* (Balsiger et al. 1995, Eberhardt et al. 1995). Isotopic ratios are crucial probes for the history of Solar System material. However, isotopic effects for oxygen are small: $\delta\ ^{18}O$ = 40 $^0/_{00}$ at most (as in some meteoritic inclusions, Clayton 2003). The limited sensitivity of our observation and the uncertainty of our excitation model precludes us to detect such an effect.

4. Conclusions

We have observed the fundamental rotational line of water in four comets with Odin. Water production rates were derived using a state-of-the-art excitation model. They are consistent with those obtained with other methods. The model also agrees with maps of the water line and with the line shapes observed at high resolution. This shows that such observations could be used to retrieve reliable water production rates. $H_2^{18}O$ was also detected for the first time in a comet by remote sensing, confirming that no strong $^{16}O/^{18}O$ isotopic anomaly is present.

In the future, other space facilities will be able to observe radio lines of cometary water. With the heterodyne instrument *HIFI* aboard the *Herschel Space Observatory*, comets with $Q[H_2O] = 10^{27}$ s^{-1} could be easily detected (Bockelée-Morvan & Crovisier 2001). Water isotopes (and especially HDO) could be searched for in moderately active comets. Several rotational lines could be observed almost simultaneously, allowing us to probe the excitation state of water and the physical conditions of cometary atmospheres. Aboard the *Rosetta* space probe, the small radio telescope *MIRO* (Gulkis et al. 2003) will observe the 1_{10}–1_{01} lines of $H_2^{16}O$, $H_2^{17}O$ and $H_2^{18}O$ in the close environment of a cometary nucleus.

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