Hunt for Molecules
F. Combes, F. Casoli, E. Falgarone, L. Pagani (eds)

MOLECULES IN COMETS WITH ODIN AND DEEP IMPACT OBSERVATIONS

Biver, N.[1] and the Odin Team[2]

Abstract. The Odin satellite has been used to observe the 557 GHz line of water with high spectral resolution in 12 comets between 2001 and 2005. Accurate measurements of the water production rates have been achieved and were essential to obtain abundances of other molecules relative to water. Thanks to Odin's frequency coverage, it has been also possible to detect the $H_2^{18}O$ 548 GHz line in four comets. The $^{16}O/^{18}O$ isotopic ratio (≈ 450) is consistent with the terrestrial value. Ammonia was tentatively detected in C/2001 Q4 and C/2002 T7 with an abundance relative to water ($\approx 0.5\%$) similar to values generally measured at other wavelengths. In June–August 2005, Odin also participated actively in the observing campaign of comet 9P/Tempel 1 at the time of the NASA mission Deep Impact encounter. The water line was regularly detected and variations of line shape and outgassing rate were found.

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[1] LESIA, CNRS UMR 8109, Obs. de Paris, 5 pl. Jules Janssen, 92190 Meudon, France

[2] Odin is a Swedish-led satellite project funded jointly by the Swedish National Space Board (SNSB), the Canadian Space Agency (CSA), the National Technology Agency of Finland (Tekes) and the Centre national d'études spatiales (CNES, France). The Swedish Space Corporation is the prime contractor, also responsible for Odin operations.

1 Introduction

Water is the main constituent of the ices of cometary nuclei. The study of cometary water is thus crucial for cometary science. Measurements of water production rates allow us to determine the relative abundances of cometary volatiles. Several molecules can be observed in the ultraviolet, infrared and radio domains, but the opacity of the Earth's atmosphere precludes the observation of water from the ground, except for weak lines arising from highly excited rovibrational states. The first observation of the H_2O ($1_{10}-1_{01}$) fundamental line of water at 556.936 GHz in a comet was obtained by the Submillimeter Wave Astronomical Satellite (SWAS, Neufeld et al. 2000) in 1999. We report here observations of this line with the Odin satellite in 12 comets. These observations were complemented with observations of $H_2^{18}O$ and NH_3 in the brightest of these objects. The present paper is adapted from Biver et al. (2006b) where the Odin cometary observations are reported in more details.

2 The Odin Satellite

The Odin satellite (Nordh et al. 2003) was launched on 20 February 2001 on a Sun synchronous polar orbit. Odin houses a 1.1-m radiometer equipped with 5 receivers at 119 GHz and covering the 486–504 GHz and 541–580 GHz band domains that are in large part unobservable from the ground. Half of the time is dedicated to astronomical studies and the other half to aeronomical investigations. The main astronomical objectives are to search for O_2 and H_2O isotope emission in the Universe, from the Solar System to galaxies. Odin is well suited for comet studies: it is equipped with single side-band receivers with system temperatures of 3000–3500 K and two to three receivers can be used simultaneously (Frisk et al. 2003). Two receivers are covering the band of the three water isotopologues ($H_2^{16}O$, $H_2^{17}O$ and $H_2^{18}O$), and a third one can be used to observe the fundamental line of NH_3 at 572.498 GHz.

Odin is equipped with three spectrometers: a low-resolution (1 MHz) wide band (1 GHz) acousto-optical spectrometer (AOS) and two high-resolution (176 kHz, reduced to 202 kHz after 2002) autocorrelators. High resolution (corresponding to 95–110 m s^{-1} at 557 GHz) is essential to resolve cometary lines. The Odin beam at 557 GHz is 2.2' and the main beam efficiency is about 0.85.

3 Comet observations

We choose to mainly target the comets that were potentially active enough for in-depth chemical investigations from ground-based and space observatories. Several comets came close enough to the Earth ($\leq$0.4 AU) with an outgassing rate large enough to undertake detailed studies. When possible, the Odin observations were coordinated with other radio observations: with OH observations at 18 cm with the Nançay radio telescope for the long-term monitoring of the water production rate and for assessing water and OH modelling (Colom et al. 2004); with millimetre and submillimetre molecular observations with the Caltech Submillimeter Observatory (CSO) 10-m and the Institut de Radioastronomie Millimétrique (IRAM) 30-m observatories (Biver et al. 2006a), to obtain molecular abundances relative to water. Table 1 summarizes the observations of comets conducted with Odin and their main results. One of the major interests of Odin is to put into evidence the asymmetry of the 557 GHz water line in cometary atmospheres (e.g. Fig. 1). This is due to its optical thickness and self-absorption by the cooler coma in the foreground. Line intensities have been converted into production rates. A Haser model with spherical outgassing and constant radial expansion velocity is used to describe the density. Constant temperature throughout the coma, collisions with neutrals, electrons, radiative excitation and self absorption due to opacity are taken into account for excitation of water energy levels (see Biver et al. 2006b for further details). The code can simulate line profiles that are generally in good agreement with observed lines.

Odin was used to monitor the gaseous activity of several comets and study its evolution with time and distance to the Sun. An example of evolution of water outgassing rate in comet C/2003 K4 (LINEAR) is shown in Fig. 2.

4 Comet maps

Nine point maps, with typically 1' spacing, were acquired on most comets in order to determine the position of the true centre of brightness. The offset with respect to the expected position was generally less than 20" and due to the limited accuracy of the telescope pointing. Wider maps (7×7' or more) were obtained on bright comets C/2001 A2, C/2000 WM_1, 153P (Lecacheux et al. 2003) and C/2001 Q4 (Hjalmarson et al. 2005). Mapping

Table 1. Comet observations with Odin

Dates of observations [yyyy/mm/dd.d]	$< r_h >$ [AU]	$< \Delta >$ [AU]	$Q_{\mathrm{H_2O}}$ [10^{28} molec. s^{-1}]	Notes
Comet C/2001 A2 (LINEAR)				
2001/04/27.3	0.94	0.83	9.2 ± 0.8	
2001/06/20.5–07/09.4	0.94–1.16	0.24–0.28	11.2–4.0	maps
Comet 19P/Borrelly				
2001/09/23.4, 11/05.5	1.36, 1.48	1.47, 1.34	3.3, 2.3	*Deep Space 1*
Comet C/2000 WM$_1$ (LINEAR)				
2001/12/07.9	1.12	0.34	4.2 ± 0.9	map
2002/03/12.6	1.17	1.24	6.7 ± 0.5	
Comet 153P/2002 C1 (Ikeya-Zhang)				
2002/04/22.2	0.92	0.42	26.3 ± 1.0	map
2002/04/24.6–28.2	0.96–1.02	0.41	19.5–15.7	$H_2^{18}O$
Comet C/2002 X5 (Kudo-Fujikawa)				
2003/03/03.4–30.6	0.90–1.53	0.93–1.54	2.7–0.6	
Comet 29P/Schwassmann-Wachmann 1				
2003/06/23.6–29.4	5.75	5.31	< 2.3	
Comet 2P/Encke				
2003/11/16.7, 23.7	1.01, 0.90	0.26, 0.27	0.44, 0.65	
Comet C/2001 Q4 (NEAT)				
2004/03/06.6–04/13.6	1.52–1.11	1.73–0.79	13.8–21.3	
2004/04/26.7–02/02.6	1.02–0.99	0.45–0.35	21.2 ± 1.5	$H_2^{18}O$, NH_3
2004/05/16.0	0.96	0.44	17.6 ± 1.0	map
Comet C/2002 T7 (LINEAR)				
2004/01/26.6, 02/01.7	1.76, 1.67	1.86, 1.91	25.0, 22.5	
2004/05/24.1–27.6	0.93	0.41	17.8 ± 1.6	$H_2^{18}O$, NH_3
2004/05/29.2	0.97	0.49	16.2 ± 1.8	
Comet C/2003 K4 (LINEAR)				
2004/11/27.7–12/28.7	1.27–1.60	1.40–1.16	18.2–12.2	
2005/01/05.7–02/19.7	1.69–2.23	1.23–2.25	11.4–3.2	
Comet C/2004 Q2 (Machholz)				
2005/01/17.8–23.8	1.21	0.40	22.7 ± 0.8	$H_2^{18}O$
Comet 9P/Tempel 1				
2005/06/18.2, 23.7	1.52, 1.51	0.82, 0.84	1.1, 1.2	
2005/07/03.5–05.8	1.51	0.90	0.7–1.0	*Deep Impact*
2005/07/07.7–08/07.7	1.51–1.54	0.91–1.12	1.0–0.5	

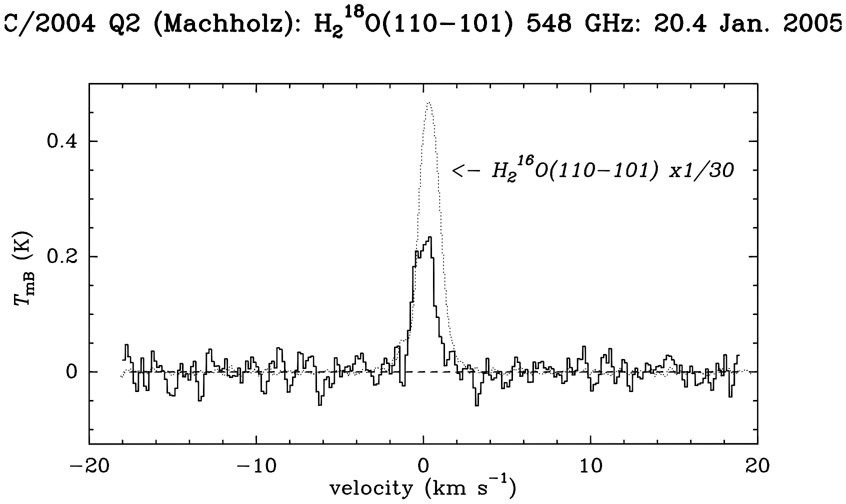

Fig. 1. The 547.7 GHz $H_2^{18}O$ line observed with Odin in comet C/2004 Q2 (Machholz): average of 17.8 to 23.8 January data. Dotted line: the 556.9 GHz $H_2^{16}O$ line observed during similar time interval (17.8–21.8 Jan.), scaled down by a factor of 30.

the H_2O emission in cometary comae provides useful constraints for an accurate determination of the water production rate. Indeed, the change in intensity and velocity shift of the line with offset constrains the water excitation mechanism and line optical thickness.

5 Observations of the $H_2^{18}O$ isotopologue

$H_2^{18}O$ was first observed in comet 1P/Halley via mass spectroscopy (Balsiger et al. 1995, Eberhardt et al. 1995). Its first remote spectroscopic detection was obtained with Odin on comet 153P/Ikeya-Zhang in 2003 (Lecacheux et al. 2003). The $1_{10} - 1_{01}$ transition at 547.676 GHz was subsequently securely detected in C/2001 Q4 (NEAT) (Hjalmarson et al. 2005), C/2002 T7 (LINEAR) and C/2004 Q2 (Machholz) (Fig. 1). From these spectra, we can readily see the difference in shape between the optically thin line of $H_2^{18}O$ and the optically thick $H_2^{16}O$ line which is redshifted by about 0.3 km s^{-1}.

The $^{16}O/^{18}O$ isotopic ratios in cometary water can be estimated from the $Q_{H_2^{16}O}/Q_{H_2^{18}O}$ ratio. The following values are measured (Lecacheux et al. 2003, Biver et al. 2006b):

- Comet 153P: $^{16}O/^{18}O = 450 \pm 50$
- Comet C/2001 Q4: $^{16}O/^{18}O \approx 440 \pm 70$
- Comet C/2002 T7: $^{16}O/^{18}O \approx 470 \pm 80$
- Comet C/2004 Q2: $^{16}O/^{18}O = 440 \pm 25$

Our measurements in four comets ($\approx$ 450) are consistent with the terrestrial $^{16}O/^{18}O$ ratio (499) or a moderate ^{18}O enrichment. But imperfection in the modelling of the $H_2^{16}O$ line makes the determination of the $^{16}O/^{18}O$ ratio to be possibly slightly underestimated.

6 Observations of ammonia

NH_3 photodissociative lifetime (6700 s at 1 AU from the Sun) is short and the search for ammonia was only worth attempting in comets close to the Earth. The $J_K = 1_0 - 0_0$ ammonia line at 572.498 GHz was searched for with Odin in comets C/2001 Q4, C/2002 T7 and C/2004 Q2, which all came within 0.4 AU to the Earth. The line was marginally detected in C/2001 Q4 and C/2002 T7. The corresponding production rates relative to water are $0.54 \pm 0.10\%$ and $0.40 \pm 0.09\%$ respectively (Biver et al. 2006b). These abundances are similar to values measured in other comets from direct observations of ammonia (Bird et al. 1999) or via observation of the NH_2 radical in the visible ($\sim$ 0.5%, Kawakita and Watanabe 2002). They are also consistent with the upper limits obtained in the same comets, from observations of the 24 GHz lines (Hatchell et al. 2005).

7 Comet 9P/Tempel 1 and Deep Impact

Observing this comet in support to the Deep Impact mission (Meech et al. 2005) was a major objective of Odin in 2005. This comet returned to perihelion on 5 July 2005 at 1.51 AU, the day after it was hit by the Deep Impact impactor (on 4.24 July 2005, A'Hearn et al. 2005). This comet, with a 5.5-year orbital period, belongs to the Jupiter family like 19P/Borrelly.

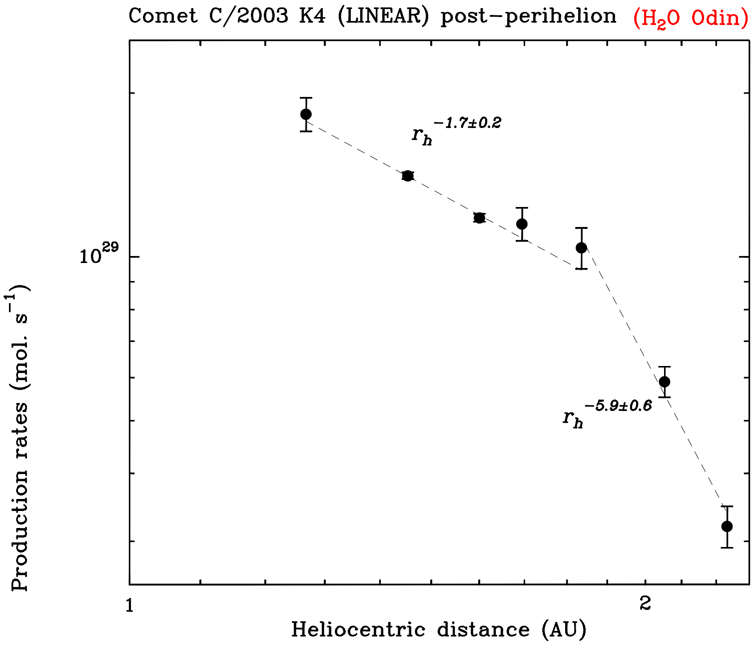

Fig. 2. The evolution of the water outgassing rate of comet C/2003 K4 (LINEAR) with heliocentric distance when the comet receded from the Sun between Nov. 2004 and Feb. 2005. Note the change of slope around 1.9 AU.

95 Odin orbits were dedicated to the monitoring of 9P/Tempel 1 water outgassing rate between 18 June and 7 August 2005 (Table 1, Biver et al. 2005b). The H_2O line was continuously monitored from 3.5 until 5.8 July (32 orbits of 96 min with 45 min pointing on the comet), and regularly observed until 7 August 2005. (Table 1). The line shows some intensity and shape variations presumably linked to the rotation of the nucleus (1.7 day, A'Hearn et al. 2005), also put into evidence in HCN production variations observed at IRAM (Biver et al. 2005a). However, the comparison of the line shapes obtained from averaging the signal over the rotation following spacecraft impact, on the one hand, and using the signal from the later observations under normal activity, on the other hand, (Fig. 3) suggests an

excess of emission corresponding to the release of about 4 000 tons of water after the impact (Biver et al. 2005b).

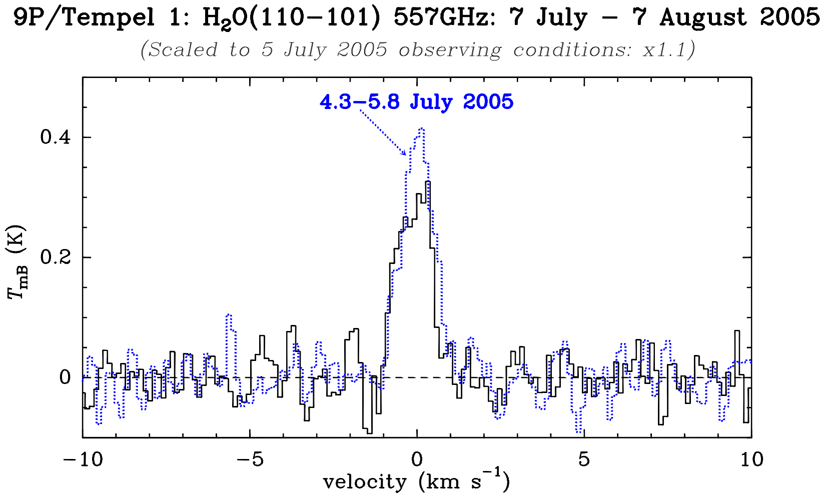

Fig. 3. The H_2O line at 557 GHz observed by Odin in comet 9P/Tempel 1 after Deep Impact collision. In dotted lines: average of observations obtained during the first rotation just following the impact. In solid lines: average of observations obtained between 7.7 July and 7.7 August, after dissipation of impact cloud. These observations were sampled and averaged to cover a full nucleus rotation and the lines were scaled to correct for the decrease of signal between the two observations, due to variation of distances to the Earth and the Sun (outgassing proportional to r_h^{-2}).

8 Conclusion

In about four years, Odin has provided us with a wealth of information on comets. It will be fundamental to improve the modelling of water emission by comets. Velocity resolved profiles of the optically thick 557 GHz line were obtained: H_2O self-absorption is observed and manifests itself as a red-shift of the line which varies throughout the coma. Variations of the gas expansion velocity with heliocentric distance and outgassing rate have been measured from the line widths. The evolution of the water production rate with time and heliocentric distance has been monitored in several comets, especially 19P/Borrelly (Bockelée-Morvan et al. 2004) and 9P/Tempel 1 in support of space missions. The $H_2^{18}O$ 547 GHz line was detected in four comets. Comparing $H_2^{18}O$ optically thin and $H_2^{16}O$ optically thick lines provides constraints on water excitation. We deduce a $^{16}O/^{18}O$ ratio around 450, compatible with, although slightly lower than, the terrestrial value. Ammonia was detected at 572 GHz in two comets with abundance ratios (∼0.5%) similar to those measured in other comets.

In the near future the Herschel Space Observatory with its HIFI heterodyne instrument will allow to observe the full submillimetre spectrum of cometary water with high sensitivity and spatial resolution (Crovisier 2005). The MIRO experiment on board the Rosetta spacecraft (Gulkis et al. 2006) will observe in-situ the same lines of H_2O isotopes and NH_3 in the coma of comet 67P/Churyumov-Gerasimenko and provide detailed spatial information.

References

A'Hearn, M. F., Belton, M. J. S., Delamere, W. A., 2005, Science, 310, 258

Balsiger, H., Altwegg, K. & Geiss, J., 1995, J. Geophys. Res., 100, 5827

Bird, M. K., Janardhan, P., Wilson, T. L. et al., 1999, Earth, Moon, and Planets, 78, 21

Biver, N., Bockele-Morvan, D., Colom, P. et al., 2005a, IAU Circ. 8538, 1

Biver, N., Bockele-Morvan, D., Boissier, J., et al. 2005b, BAAS, 37, 710

Biver, N., Bockelée-Morvan, D., Crovisier, J., et al., 2006a, A&A, *in press*

Biver, N., Bockelée-Morvan, D., Crovisier, J., et al., 2006b, *submitted to Planet. Space Sci.*

Bockelée-Morvan, D., Biver, N., Colom, P., et al., 2004, Icarus, 167, 113

Colom, P., Biver, N., Lecacheux, A., Crovisier, J. & Bockelée-Morvan, D., 2004, In: Combes, F. et al. (Ed.), *SF2A Scientific Highlights 2004*, EdP-Sciences Conference Series, 69

Crovisier, J., 2005, In: Wilson, A. (Ed.), *Proceedings of the dusty and molecular universe: a prelude to Herschel and ALMA*, ESA SP-577, 145

Eberhardt, P., Reber, M., Krankowsky, D. & Hodges, R. R., 1995, A&A, 302, 301

Frisk, U., Hagström, M., Ala-Laurinaho, J. et al., 2003, A&A, 402, L27

Gulkis, S., Allen, M., Backus, C., et al., 2006, *submitted to Planet. Space Sci.*

Hatchell, J., Bird, M. K., van der Tak, F. F. S. & Sherwood, W. A., 2005, A&A, 439, 777

Hjalmarson, Å., Bergman, P., Biver, N. et al., 2005, Advances in Space Research, 36, 1031

Kawakita, H. & Watanabe, J., 2002, ApJ, 572, L177

Lecacheux, A., Biver, N., Crovisier, J. et al., 2003, A&A, 402, L55

Meech, K. J., and 208 coauthors, 2005, Science, 310, 265

Neufeld, D.A., Stauffer, J.R., Bergin, E.A. et al., 2000, ApJ, 539, L151

Nordh, H.L., von Schéele, F., Frisk, U. et al., 2003, A&A, 402, L21