OBSERVATIONS OF THE OH RADICAL IN COMET C/1995 O1 (HALE–BOPP) WITH THE NANÇAY RADIO TELESCOPE

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Abstract. We present OH 18-cm observations of comet Hale–Bopp (C/1995 O1) at the Nançay radio telescope. On nucleus and offset position observations allowed us to obtain both OH production rates and quenching radii. The maximum OH production rate was reached around perihelion, at about 10^{31} s^{-1}.

Keywords: Comets, OH radical, radio astronomy, C/1995 O1 (Hale–Bopp)

1. Introduction

The 18-cm lines of the OH radical were observed in C/1995 O1 with the Nançay radio telescope between August 1995 and September 1997. Since the first detection in April 1996 (Crovisier et al. 1996), the comet was monitored and OH production rates, as well as gas expansion velocities were obtained (Biver et al., 1997a).

Besides providing regular measurements of the water production rate, the Hale–Bopp campaign was useful to test existing models of the OH maser quenching because the comet underwent such a huge activity, never seen before. For this, we undertook a rough mapping by observing at offset positions several beamwidths (3.5′) from the nucleus together with the centre position, between October 1996 and July 1997. The OH line intensity at the centre was sometimes *less* than those at offset positions, providing direct evidence for collisional quenching of the OH maser in the inner coma.

2. Observations

Comet C/1995 O1 Hale–Bopp was observed with the same technique previously used for comet P/Halley and other comets (Gérard et al., 1989, Bockelée-Morvan

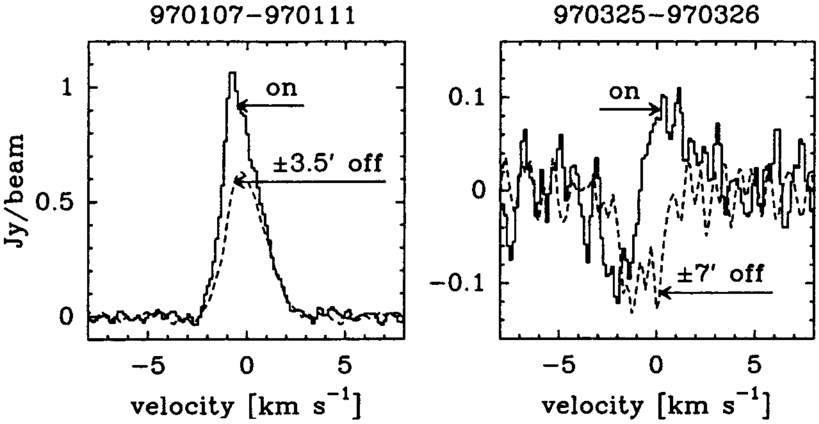

Figure 1. Left: spectrum averaged between 7 and 11 January, 1997. Average of both polarizations, 1667 and 1665 MHz lines scaled to 1667 MHz assuming the LTE ratio of 9/5. The heliocentric radial velocity of the comet is -21.8 km s^{-1}, such that the OH profile is in emission (Despois et al., 1981). Right: 25 and 26 March, 1997, averaged spectra. The on nucleus spectrum (solid line) shows an S-shape, while the offset position (dashed line), less affected by quenching, shows the maser absorption only (see text).

et al., 1990). The telescope has a RA $\times$ dec beam of $3.5' \times 19'$ at dec = 0°. A rough mapping of the OH coma was made by observing the nucleus and offset positions up to 3 beams East and West. A 1024-channel spectrometer split into 4 $\times$ 256 channels yields a velocity spacing of 0.14 km s^{-1} (782 Hz). The standard procedure consists in observing the main OH lines at 1667 and 1665 MHz in both left- and right-circular polarizations to detect a possible Zeeman effect. Figure 1 (left) shows a typical profile averaged on 7–11 January, 1997.

3. Deriving OH Production Rates

The determination of the OH production rate involves several steps (Despois et al., 1981). The OH density modelling is done in the Haser-equivalent frame (Combi and Delsemme, 1980). The inversion models of the Λ-doublet are those of Despois et al. (1981) and Schleicher and A'Hearn (1988). The H_2O expansion velocity is determined from the actual OH line shape (averaged over several days to improve the signal-to-noise ratio) by the trapezoid method (Bockelée-Morvan et al., 1990): the OH ejection velocity is 1.05 km s^{-1} (Crovisier, 1989) and the resulting expansion velocity varied between $v_n \simeq 0.7$ km s^{-1} at r_h = 3 AU and $v_n \simeq 2.2$ km s^{-1} at r_h = 0.93 AU, with r_h the heliocentric distance. This latter value is much larger than that deduced from millimetre lines near perihelion ($\simeq$1.1 km s^{-1}, Biver et al., 1997b) which sample a narrower zone in the coma. This provides a direct evidence of the *acceleration* of the gas with increasing cometocentric distance, ascribed to photolytic heating. The H_2O and OH lifetimes at 1 AU are respectively 8.2×10^4 (Crovisier, 1989) and 1.1–1.6 $\times 10^5$ s (Budzien et al., 1994) near solar minimum.

Cometary OH masers are quenched in the inner part of the coma where the ion and neutral densities are high enough that the collision rate C across the $^2\Pi_{3/2}$ J = 3/2 ground state Λ doublet exceeds its effective UV pumping rate U. The quenching radius, r_q, is defined as the distance from the nucleus at which $U = C$.

Collisional quenching is an important effect to take into account, especially when the fraction of OH molecules "seen" by the telescope is reduced significantly. There are three situations where this occurs: (i) when the geocentric distance is small, (ii) when r_h is small and (iii) when the production rate is large. Both first and second cases, which come from geometrical effects, occured in comet C/1996 B2 (Hyakutake) (Gérard et al., 1998). In the case of comet Hale–Bopp, we expect that its large production rate will produce an unusually large quenched zone: the quenching radius was indeed estimated to about 2.6×10^5 km in October and November 1996 at r_h = 2.2 to 2.7 AU (Biver et al., 1997a). Besides a very few determinations of r_q (see Gérard (1990) for comet 1P/Halley), one has to rely on scaling laws to have an estimation of this parameter. Until now, r_q was scaled according to:

$$r_q = r_q^0 r_h Q_P^{\frac{1}{2}} \tag{1}$$

(Schloerb, 1988), with r_h in units of AU, Q_P the total gas production rate, in units of 10^{29} s^{-1}. In the case of comet Hyakutake, we tried to take into account the relative variation of the ion content with the heliocentric distance, introducing a new scaling law (Gérard et al., 1998):

$$r_q = 37\,000\,\frac{Q_P}{v_n}\ \text{(km)} \tag{2}$$

where v_n, the outflow velocity in km s^{-1}, is determined from the actual OH line shape.

Instead of using such scaling laws, we have determined the OH production rate and the quenching radius from the centre exposure and the average (East, West) offset positions (the averaging takes care of (East, West) asymmetries). Letting r_q vary as a free parameter, the pair (r_q, Q_{OH}) is found where the curves $Q_{OH} = f(r_q)$ intersect (see Figure 2).

As for comet Hyakutake (Gérard et al., 1998), we used a progressive quenching throughout the coma (Schloerb, 1988), according to $i = i^* r^2/(r^2 + r_q^2)$, with r, the distance from the nucleus, i^* the population inversion of the OH ground state in the case of pure UV fluorescence, and i the actual inversion reduced by collisions with ions. The spontaneous emission term due to *all* OH molecules is now considered in the transfer equation (see Equation (9) in Despois et al., 1981) because it is no longer negligible compared to the stimulated emission term when r_q is large and i is small.

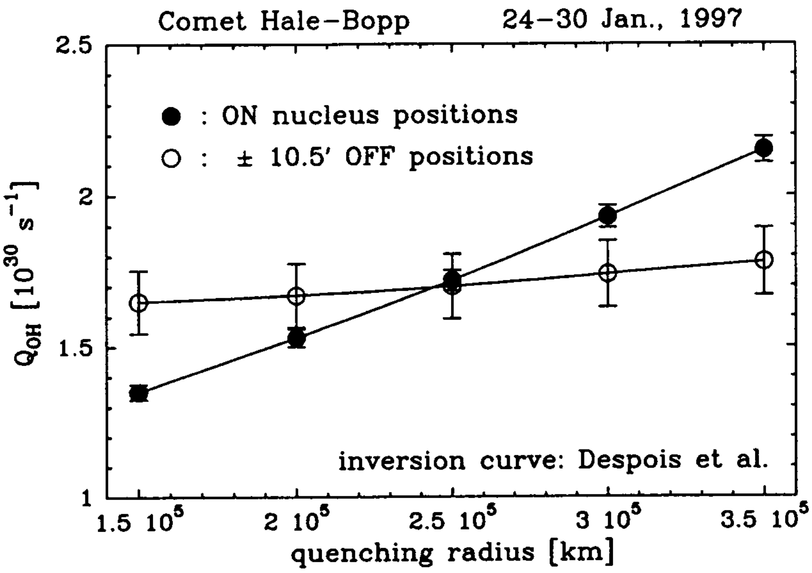

Figure 2. Determination of $Q_{\rm OH}$ and r_q. The offset position spectra are less sensitive to the quenching, the slopes of the $Q_{\rm OH} = f(r_q)$ curves are then different. At the crossing point, we obtain a consistent value of $Q_{\rm OH}$ for both centred and offset positions, and the quenching radius as a by product.

The calculations are made using the Despois et al. (1981) and Schleicher and A'Hearn (1988) inversion curves. The results are given in Table I and illustrated in Figure 3. The maximum OH production rate was reached around perihelion, at $\simeq 10^{31}$ s^{-1}.

4. Discussion

Looking at the quenching radii in Table I, it seems that Equation (1) underestimates the quenching radius (with r_q^0 = 40 000 km from our October–November Hale–Bopp data (Biver et al., 1997a), in agreement with the value measured in 1P/Halley (Gérard, 1990)), while Equation 2 overestimates this parameter. This suggests that ions played a major role in the OH collisional quenching near perihelion. But due to the exhaustion of neutrals beyond the ionization scale length (in fact when Q_P exceeds $\simeq 10^{30}$ s^{-1}), the expected linear dependence on Q_P (Equation (2)) should not apply and be replaced by a weaker Q_P dependence (Schmidt and Wegmann, 1982). This indeed happened for this comet.

Last but not least, the ion quenching of the OH coma must be anisotropic as evidenced by both the contour maps of the bow shock and ion column density calculated by Wegmann et al. (1987). The quenching should be stronger in the antisunward hemisphere than in the sunward hemisphere of the OH coma, resulting

TABLE I

C/1995 O1 (Hale–Bopp): OH production rate and quenching radius, given by the comparison between the on and offset positions. Production rates are estimated without assumption about any quenching scaling law. The pair (r_q, Q_{OH}) is found where the curves $Q_{OH} = f(r_q)$ intersect. Uncertainties in both r_q and Q_{OH} come from the extremum values permitted by the intersection of the curves within error bars

Date 1997	r_h AU	i Despois et al. r_q 10^3 km	i Despois et al. Q_{OH} 10^{30} s^{-1}	i Schleicher & A'Hearn r_q 10^3 km	i Schleicher & A'Hearn Q_{OH} 10^{30} s^{-1}
January 01–11	1.67	289^{+32}_{-34}	1.34 ± 0.08	290^{+30}_{-28}	$1.39^{+0.08}_{-0.07}$
January 15–22	1.52	286^{+24}_{-22}	$1.84^{+0.09}_{-0.08}$	285^{+26}_{-22}	$1.89^{+0.09}_{-0.08}$
January 24–30	1.42	244 ± 43	1.70 ± 0.14	244^{+44}_{-43}	$1.71^{+0.15}_{-0.13}$
February 04–09	1.30	317^{+64}_{-48}	$2.42^{+0.33}_{-0.23}$	321^{+61}_{-57}	$2.39^{+0.32}_{-0.26}$
February 14–16	1.20	≥ 491	≥ 4.17	≥ 486	≥ 3.97
February 20–28	1.11	358^{+69}_{-63}	$3.40^{+0.44}_{-0.39}$	359^{+97}_{-59}	$3.84^{+0.69}_{-0.38}$
March 01–07	1.04	359^{+141}_{-45}	$2.72^{+0.86}_{-0.24}$	340^{+228}_{-43}	$3.70^{+1.77}_{-0.39}$
March 20–21	0.93	864^{+130}_{-166}	$8.57^{+3.53}_{-2.96}$	948^{+147}_{-200}	$8.14^{+3.56}_{-3.05}$
March 22–23	0.93	907^{+111}_{-161}	$11.10^{+4.8}_{-4.07}$	989^{+125}_{-188}	$10.30^{+4.60}_{-3.99}$
March 28–29	0.92	874^{+102}_{-78}	$12.70^{+3.30}_{-3.33}$	770^{+93}_{-71}	$13.10^{+3.40}_{-3.46}$
April 02–08	0.92	$950\pm$?	$9.40^{+1.50}_{-?}$	$1743^{+?}_{-918}$	$9.59^{+0.91}_{-2.39}$
May 23–31	1.34	$346^{+?}_{-178}$	$1.86^{+?}_{-0.50}$	≥ 224	≥ 3.59
June 13–29	1.65	266^{+434}_{-135}	$0.85^{+0.74}_{-0.18}$	$449^{+?}_{-271}$	$3.18^{+?}_{-0.86}$
July 01–13	1.84	51^{+161}_{-51}	$0.55^{+0.12}_{-0.06}$	62^{+296}_{-62}	$1.89^{+0.62}_{-0.22}$

in an apparent excess outgassing towards the Sun. This was likely observed in comet Hale–Bopp within 2 AU from the Sun (Biver et al., 1997a).

The spectra observed on 25–26 March 1997 (Figure 1, right) provide the first direct evidence of OH spontaneous emission in a comet. Since the mean population inversion was −0.2, the profile should be in absorption as seen on the offset exposures. However, on the centred exposure, where the quenching is very strong, the spontaneous emission becomes comparable to the stimulated emission and explains the S-shape curve.

Pre-perihelion OH production rates have shown first a steep increase with $Q_{OH} \sim r_h^{-6.8}$. At $r_h \simeq 3$ AU, the slope appeared to break down and became

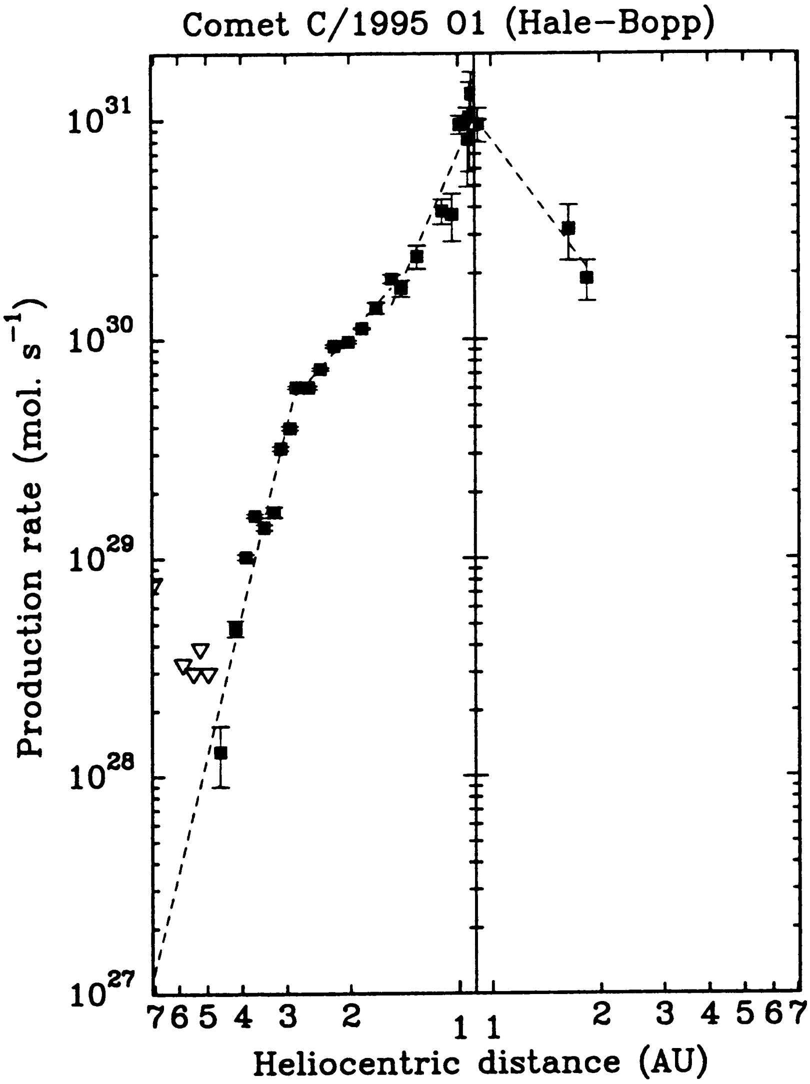

Figure 3. OH production rate as a function of heliocentric distance. The inversion parameter i comes from Schleicher and A'Hearn (1988).

$\sim r_h^{-1.8}$. Finally, when approaching perihelion ($r_h \leq 1.3$ AU), the slope rose again up to $\sim r_h^{-3.7}$. The long-term evolution of the water production rate, traced by Q_{OH}, can be compared with that of other parent species (cf. Figure 3 in Biver et al., 1997b). It provides crucial constraints to sublimation models of the comet nucleus (Bockelée-Morvan and Rickman, 1997).

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