THE 1995-2002 LONG-TERM MONITORING OF COMET C/1995 O1 (HALE-BOPP) AT RADIO WAVELENGTHS

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Abstract. The bright comet Hale-Bopp provided the first opportunity to follow the outgassing rates of a number of molecular species over a large range of heliocentric distances. We present the results of our observing campaign at radio wavelengths which began in August 1995 and ended in January 2002. The observations were carried out with the telescopes of Nançay, IRAM, JCMT, CSO and, since September 1997, SEST. The lines of nine molecules (OH, CO, HCN, CH_3OH, H_2CO, H_2S, CS, CH_3CN and HNC) were monitored. CS, H_2S, H_2CO, CH_3CN were detected up to r_h = 3–4 AU from the Sun, while HCN and CH_3OH were detected up to 6 AU. CO, which is the main driver of cometary activity at heliocentric distances larger than 3–4 AU, was last detected in August 2001, at $r_h = 14$ AU.

The gas production rates obtained from this programme contain important information on the nature of cometary ices, their thermal properties and sublimation mechanisms. Line shapes allow to measure gas expansion velocities, which, at large heliocentric distances, might be directly connected to the temperature of the nucleus surface. Inferred expansion velocity of the gas varied as $r_h^{-0.4}$ within 7 AU from the Sun, but remained close to 0.4 km s^{-1} further away. The CO spectra obtained at large r_h are strongly blueshifted and indicative of an important day-to-night asymmetry in outgassing and expansion velocity. The kinetic temperature of the coma, estimated from the relative intensities of the CH_3OH and CO lines, increased with decreasing r_h, from about 10 K at 7 AU to 110 K around perihelion.

Keywords: Comets, C/1995 O1 (Hale-Bopp), radio observations, molecules

1. Introduction

The exceptional comet C/1995 O1 (Hale-Bopp) provided us with an unprecedented opportunity to draw the link between distant activity of a comet and its outgassing close to the Sun. In the present paper, we summarize results of the long-term monitoring we performed from September 1995 to January 2002 at millimetre to submillimetre wavelengths. Nine molecules were followed and the heliocentric range covers $r_h = 0.9$ to 14 AU. This paper updates the previously published report of Biver et al. (1999a), which covers observations until January 1998. All details on the observational and analysis procedures will not be recalled here.

2. Observations

Comet Hale-Bopp has been observed on a regular basis since September 1995, with the IRAM radio telescopes (30-m single dish at Pico Veleta and the 15-m antennas of the Plateau-de-Bure interferometer used in single dish mode), and the JCMT and CSO submillimetre telescopes atop Mauna Kea, Hawaii. Since September 1997 and until January 2002, observations have been carried out at SEST in Chile, due to the negative declination of the comet. Half-power beam widths ranged from 10" to 55", depending on the antenna and observing frequency. This long-term monitoring concerns CO, CH_3OH, HCN, H_2S, H_2CO, CS, CH_3CN, and HNC. Their first detections were obtained between 6.7 AU for CO (Jewitt et al., 1996; Biver et al., 1996) and 2.4 AU for HNC (Bockelée-Morvan et al., 1996), as summarized in Biver et al. (1997). Since the report made by Biver et al. (1999a) concerning observations

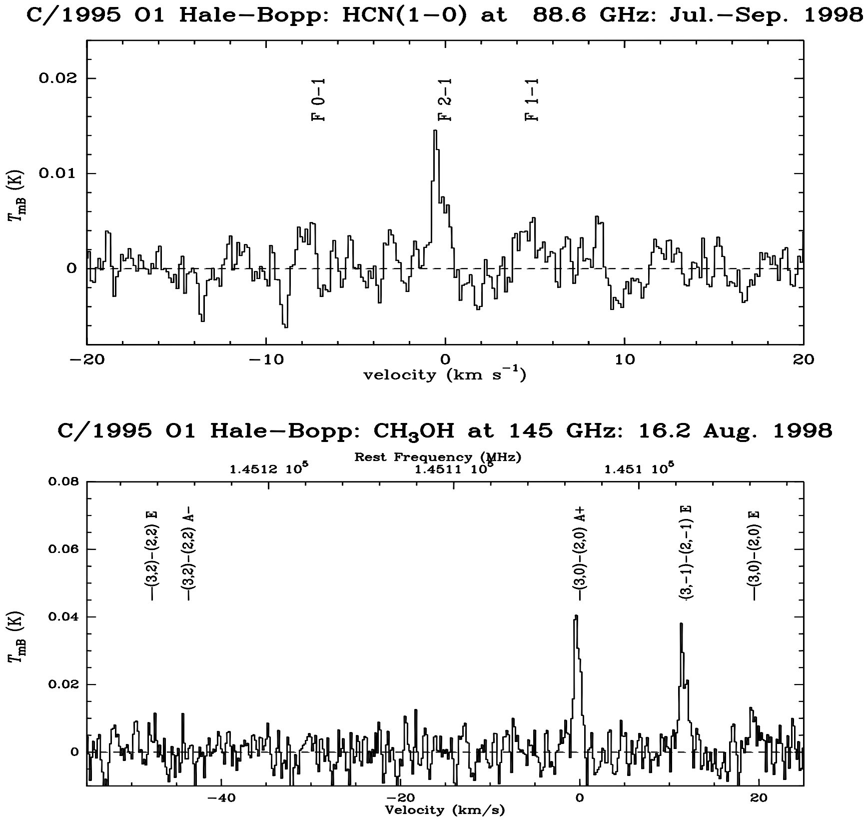

Figure 1. HCN $J(1\text{–}0)$ and CH_3OH 145 GHz spectra of comet C/1995 O1 (Hale-Bopp) observed at SEST. They correspond to the most distant detections of these molecules in any comet before. HCN was last detected in September 1998 at $r_h = 6.4$ AU and CH_3OH in August 1998 at 6.1 AU. The HCN $J(1\text{–}0)$ spectrum is the average of the last 3 runs when it was detected (July, August and September 1998).

before January 1998, the most distant detections of HCN ($r_h = 6$ AU in Sept. 1998), CH_3OH ($r_h = 6.1$ AU in Aug. 1998) and CO ($r_h = 14$ AU in Aug. 2001) in any comet were achieved (Figs 1–2). Other species fell below the detection limit at distances of 4.2 AU or less (Biver et al., 1999a).

3. Temperature and expansion velocity

The kinetic temperature of the coma and its expansion velocity are key parameters to derive accurate production rates. The simultaneous

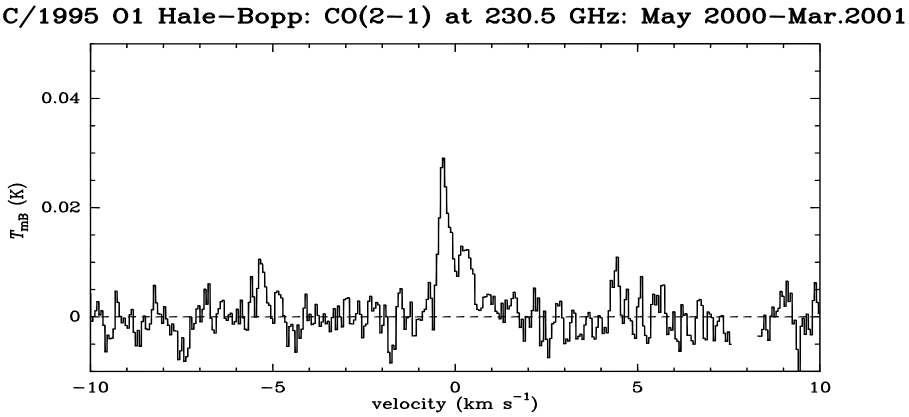

Figure 2. CO $J(2\text{–}1)$ line at 230 GHz in comet C/1995 O1 (Hale-Bopp) observed at SEST during the May 2000 – March 2001 time interval: average of 6 periods with $11 < r_h < 13$ AU.

observations of several lines of a given species can help to constrain their values. CH_3OH (304, 307, 157 and 252 GHz) and CO ($J =$ 1–0, 2–1, 3–2, 4–3) series of lines are of particular interest because their rotational temperature is very close to the kinetic temperature of the inner coma, unlike the CH_3OH (97 GHz and 145 GHz) series lines (Bockelée-Morvan et al., 1994). Figure 3 shows the evolution of the kinetic temperature from 6.5 AU to perihelion inbound and then to 7.9 AU outbound. Average of pre and post-perihelion data gives $T = 102\ (\pm 6)\ r_h^{-1.12(\pm 0.06)}$ K.

Beyond 7 AU post-perihelion, the CO $J(1\text{–}0)$ line was only marginally detected in the average of data taken at 7.9 ± 0.4 AU. Thereafter, this line was too weak to provide stringent constraints on the temperature of the coma. Taking a temperature of 5 K instead of the value of 10 K assumed for $r_h > 8$ AU, the CO production rates would be increased by about 60%. This is however going in the direction opposite to the outgassing pattern correction (cf. next Section).

The gas outflow velocity (v_{exp}) was estimated from the line shapes. As explained by Biver et al. (1999a), it was derived from the velocity at half-maximum of the lines, "half width at half maximum" ($HWHM$), on their blueshifted wing which corresponds to molecules moving preferentially from the day side of the nucleus. The evolution of this parameter, tracing the expansion velocity, is plotted in Fig. 4, as a function of heliocentric distance. Average of pre- and post-perihelion data yields $HWHM = 1.125\ (\pm 0.015)\ r_h^{-0.42(\pm 0.01)}$ km s^{-1}. The expansion velocity value we actually used to derive production rates is reduced by 10%, to take into account thermal broadening. This leads to expansion velocities on the order of 1.05 km s^{-1} at perihelion, and 0.45 km s^{-1} at 6

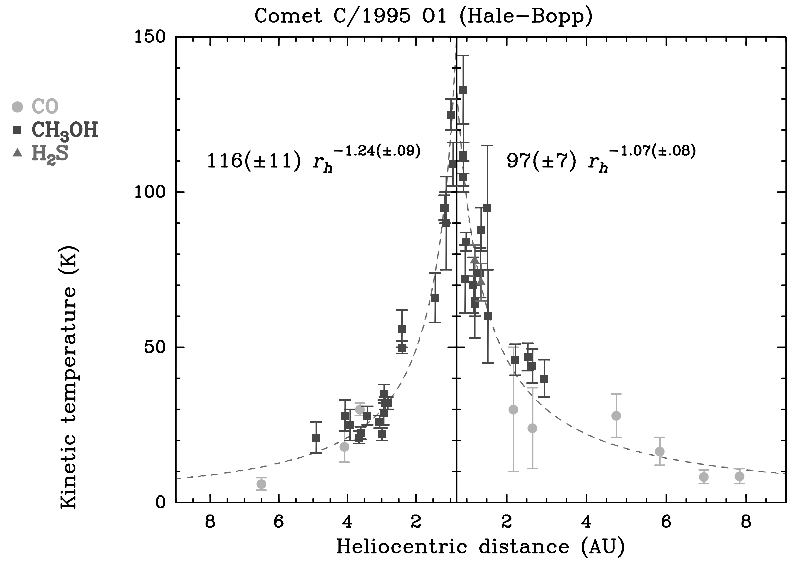

Figure 3. Evolution of the gas kinetic temperature in comet Hale-Bopp as measured from CO, H_2S and CH_3OH lines with fitted power laws (dashed lines). Left: pre-perihelion data; right: post-perihelion data.

AU, which is comparable to the value of 0.5 km s^{-1} measured in comet 29P/Schwassmann-Wachmann 1 at similar r_h (Crovisier et al., 1995).

From 7 to 14 AU after perihelion, the expansion velocity did not vary in a measurable way (Fig. 4b). From the CO line shape we actually deduce a mean value of $v_{exp} = 0.4$ km s^{-1} on the day side of the nucleus, that we used for the computation of the production rates. This velocity is intermediate between the initial CO sonic velocity expected near the surface, and the maximum velocity that the CO molecules could reach during adiabatic expansion, in case of a large fluid region (see Crifo et al., 1999). Indeed, assuming a slow-rotating body for the computation of the surface equilibrium temperature and a Bond albedo of 0.04, one computes an initial CO velocity between 0.23 and 0.19 km s^{-1} for r_h between 7 and 14 AU. Terminal velocities are 0.6 to 0.5 km s^{-1} for $r_h =$ 7 to 14 AU. The expected decrease of the velocity in $r_h^{-0.25}$, which would reflect the decrease of the surface temperature as the comet recedes from the Sun, is not clearly seen in the data, but might be within the measurement uncertainties. The actual fit $HWHM = 0.853\ r_h^{-0.25}$ shown in Fig. 4b for CO data beyond 3 AU, is relatively poor with a correlation factor $\rho = 0.51$. Note that the asymmetrical shape of the CO line profile (Fig. 2) suggests that the velocity of the CO molecules on the night side of the nucleus is smaller than that of the CO molecules on the day side. CO radio line profiles obtained in comet 29P/Schwassmann-

Wachmann 1 show similar shapes (Crovisier et al., 1995; Gunnarsson et al., 2002). The sunward/anti-sunward asymmetry in the CO velocity was attributed to a day/night asymmetry in the nucleus temperature (Crifo et al., 1999). A detailed analysis of CO Hale-Bopp spectra is to be presented by Gunnarsson et al. in a forthcoming paper.

4. Production rates

The models for converting line intensities into production rates use the previously determined temperatures and expansion velocities, with a spherically symmetric Haser density distribution. In addition, radiative decay and infrared or ultraviolet pumping by solar radiation are taken into account for all molecules (Biver et al., 1997). Photodissociative lifetimes were taken from Crovisier (1994). CS is assumed to be the photodissociation product of CS_2. H_2CO is assumed to be released from an extended source, as suggested by the comparison between observations made at centre and offset positions and from interferometric maps (Wink et al., 1999), and as observed in other comets (Colom et al., 1992; Meier et al., 1993; Biver et al., 1999b). Its parent equivalent lifetime is taken equal to 10^4 s at 1 AU.

More accurate production rates would require the modelling of the outgassing pattern using the line shapes. The asymmetry of the lines observed beyond 3 AU could be interpreted as: (i) an outgassing in a restricted cone of about 120° at a constant expansion velocity (i.e. no outgassing around the antisolar point): this would increase the production rates by 10–15%; or (ii) an outgassing at a lower rate with lower velocity towards the anti-solar point, which is more likely (Crifo et al., 1999). A two-component model with a larger expansion velocity and outgassing rate in a 45° cone along the comet-Sun direction, with respect to the remaining solid angle, would result in total outgassing rates reduced by up to 40%.

Figure 5 shows the gas production curves. Included are the OH production rates measured at Nançay from April 1996 to September 1997, as reported by Colom et al. (1999). Post-perihelion UV observations of OH (converted into water production rates) (Stern et al., 1999; Weaver et al., 1999), and infrared observations of water (Crovisier et al., 1999), are also plotted in Fig. 5.

Power law fits to the production rates are shown in Fig. 5. The pre-perihelion data have been split into 3 periods which show different trends for most molecules. Post-perihelion data do not show such distinct regimes.

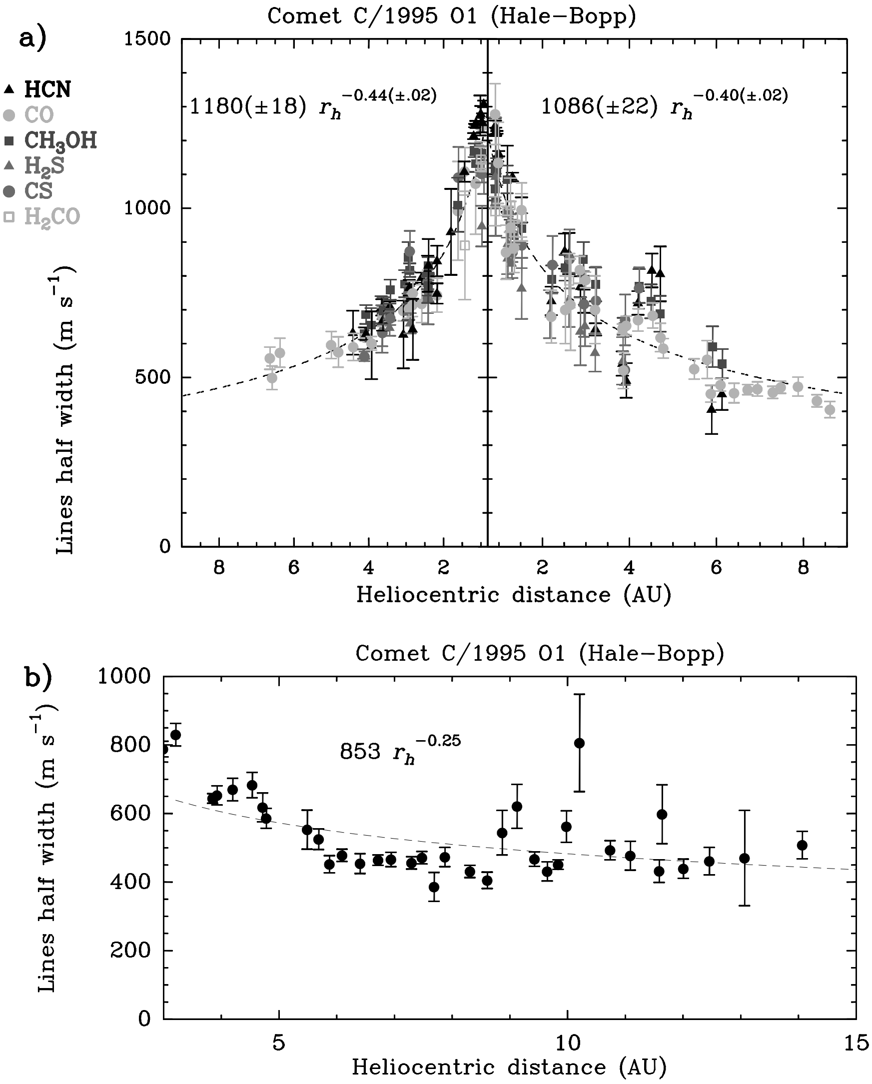

Figure 4. Upper plot: velocity at half-maximum on the blue wing of the lines, which provides an estimate of the gas expansion velocity in comet Hale-Bopp. Fitted power laws are superimposed. Lower plot: velocity at half-maximum on the blue wing of the CO lines, beyond 3 AU post-perihelion. A power law fit to these data is shown, but there are large deviations that suggest two distinct regimes, below and beyond 7 AU.

- CO is the most volatile species and showed a moderate increase of its production rate at large heliocentric distances: slopes are $r_h^{-2.2}$ at $r_h > 3$ AU pre-perihelion, $r_h^{-1.9}$ at $r_h > 0.9$ AU pre-perihelion and $r_h^{-2.0}$ at $r_h > 0.9$ AU post-perihelion. Between 3 and 1.6 AU inbound, the CO production rate stalled or even decreased before exhibiting a steep increase: this stagnation is present in numerical simulations of comet Hale-Bopp's CO production (Enzian et al., 1998). Beyond 6 AU post-perihelion, the CO production rate decreased as r_h^{-2} in average, but exhibited some significant scatter. This heliocentric evolution is not yet well simulated by thermal models of comet Hale-Bopp nucleus (Capria et al., 2000).

- CH_3OH, HCN, CH_3CN, and H_2S molecules are less volatile and less abundant than CO. However, at large heliocentric distances, they are still overabundant with respect to water, when compared to their abundances near perihelion. There are not enough data points for H_2S and CH_3CN to distinguish distinct behaviours with respect to CH_3OH and HCN. Beyond 3 AU, all these species exhibit heliocentric variations similar to CO, although slightly steeper. Upper limits obtained for CH_3OH and HCN at 6.6 AU pre-perihelion and around 7 AU post-perihelion suggest that slopes may have been steeper beyond ≈ 6 AU than below. Post-perihelion CN production rates obtained by Rauer et al. (2002) show a similar change of slope at large r_h. This is the behaviour that one would expect for a compound with the volatility of pure HCN or CH_3OH ices ($T_{\mathrm{sublimation}} \approx 100$ K).

The production rates of CS (tracing CS_2), H_2CO and HNC displayed a much steeper evolution with heliocentric distance when compared to other species, though their volatility is similar.

- The CS/HCN ratio varied as $r_h^{-0.7}$, as observed in comet C/1996 B2 (Hyakutake) (Biver et al., 1999b) and other comets (Biver et al., 2002). The origin of this variation is unexplained, but may be linked to the presence of a distributed source of CS other than CS_2.

- The HNC/HCN ratios increased with decreasing r_h with a slope of -1.1, questioning the nuclear origin of this species. In the case of this highly productive comet, Irvine et al. (1999) and Rodgers and Charnley (1998) invoked the formation of HNC from chemical reactions in the coma involving HCN.

- H_2CO/HCN increased as $r_h^{-1.5}$ beyond 1.5 AU from the Sun. This suggests that the H_2CO source may be much less volatile than

H_2CO itself. An alternative explanation is that H_2CO comes from the thermal degradation of polymers on grains (Cottin et al., 2001). The increased efficiency of this process close to the Sun, together with the increasing grain production, at least qualitatively agrees with the observed evolution of the H_2CO production rate with r_h.

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References

Biver, N., Rauer, H., Despois, D. et al.: 1996, "Substantial Outgassing of CO from Comet Hale-Bopp at Large Heliocentric Distance", *Nature*, **380**, 137–139

Biver, N., Bockelée-Morvan, D., Colom, P., et al.: 1997, "Evolution of the Outgassing of Comet Hale-Bopp (C/1995 O1) from Radio Observations", *Science*, **275**, 1915–1918

Biver, N., Bockelée-Morvan, D., Colom, P., et al.: 1999a, "Long-term Evolution of the Outgassing of Comet Hale-Bopp from Radio Observations", *Earth, Moon, and Planets*, **78**, 5–11

Biver, N., Bockelée-Morvan, D., Crovisier, J., et al.: 1999b, "Spectroscopic Monitoring of Comet C/1996 B2 (Hyakutake) with the JCMT and IRAM Radio Telescopes", *Astron. J.*, **118**, 1850–1872

Biver, N., Bockelée-Morvan, D., Crovisier, J., et al.: 2002, "Chemical Composition Diversity among 24 Comets Observed at Radio Wavelengths", *Earth, Moon, and Planets, these proceedings*

Bockelée-Morvan, D., Crovisier, J., Colom, P. and Despois, D.: 1994, "The Rotational Lines of Methanol in Comets Austin 1990 V and Levy 1990 XX", *Astron. Astrophys.*, **287**, 647–665

Bockelée-Morvan D., Moreno, R., Biver, N., et al.: 1996, "Comet C/1995 O1 (Hale-Bopp)", IAU Circular No. 6511

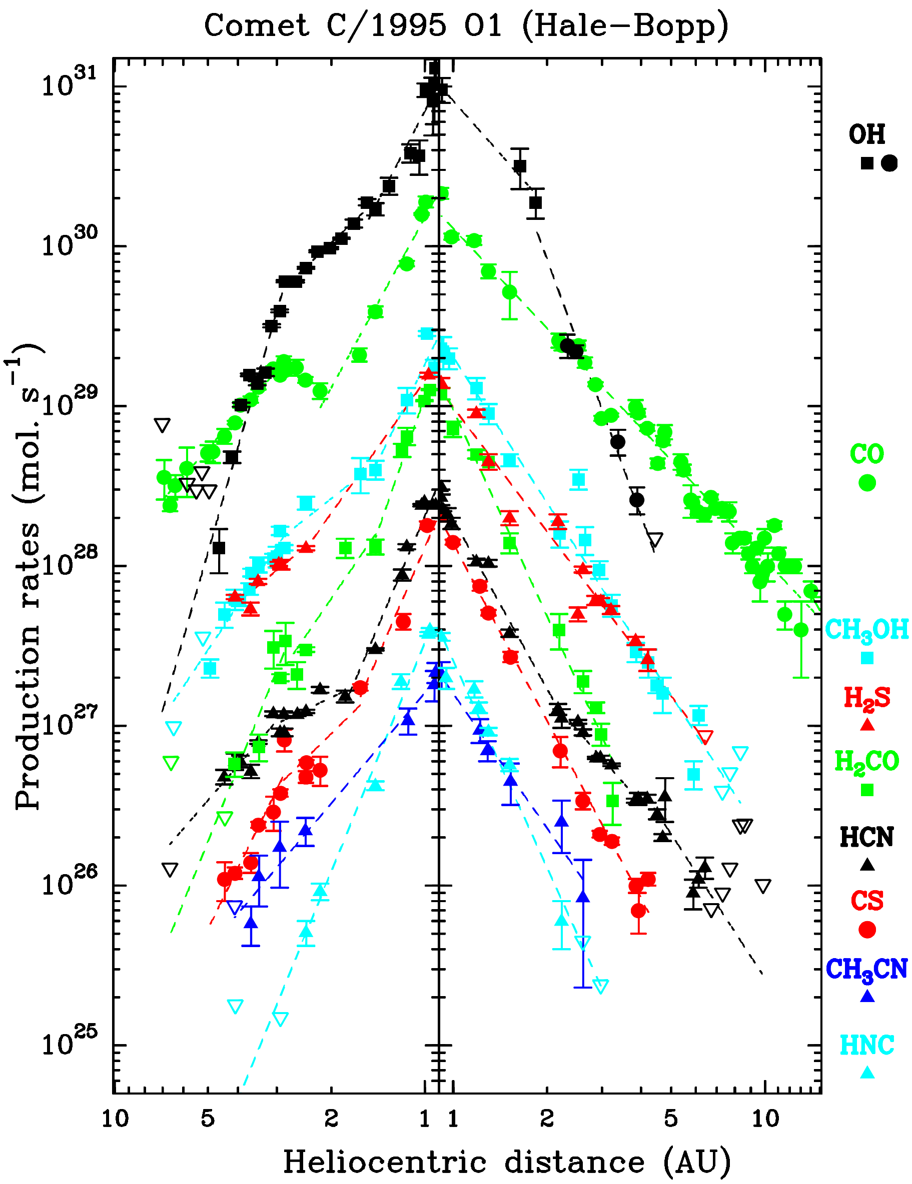

Figure 5. Evolution of production rate with heliocentric distance and fitted power laws (dashed lines). OH measurements are from Colom et al. (1999). Additional H_2O production rates measurements post-perihelion (filled circles and upper limit at 4.8 AU) are from Stern et al. (1999), Weaver et al. (1999) and Crovisier et al. (1999). Downward pointing triangles are 3-σ upper limits. Left: pre-perihelion data; right: post-perihelion data.

Capria, M.T., Coradini, A., De Sanctis, M.C., and Orosei, R.: 2000, "CO Emission Mechanisms in C/1995 O1 (Hale-Bopp)", *Astron. Astrophys.*, **357**, 359–366

Colom, P., Crovisier, J., Bockelée-Morvan, D., Despois, D. and Paubert, G.: 1992, "Formaldehyde in Comets I. Microwave Observations of P/Brorsen-Metcalf (1989 X), Austin (1990 V) and Levy (1990 XX)", *Astron. Astrophys.*, **264**, 270–281

Colom, P., Gérard, E., Crovisier, J., et al.: 1999, "Observations of the OH radical in comet Hale-Bopp with the Nançay radio telescope", *Earth, Moon, and Planets*, **78**, 37–43

Cottin, H., Gazeau, M. C., Benilan, Y. and Raulin, F.: 2001, "Polyoxymethylene as Parent Molecule for the Formaldehyde Extended Source in Comet Halley", *Astrophys. J.*, **556**, 417–420

Crifo, J.-F., Rodionov, A.V., and Bockelée-Morvan, D.: 1999, "The Dependence of the Circumnuclear Coma Structure on the Properties of the Nucleus". III. First Modeling of a CO-dominated Coma, with Application to Comets 46P/Wirtanen and 29P/Schwassmann-Wachmann 1", *Icarus*, **138**, 85–106

Crovisier, J.: 1994, "Photodestruction Rates for Cometary Parent Molecules", *J. Geophys. Res.*, **99–E2**, 3777–3781

Crovisier, J., Biver, N., Bockelée-Morvan, D. et al.: 1995, "Carbon Monoxide Outgassing from Comet P/Schwassmann-Wachmann 1", *Icarus*, **115**, 213–216

Crovisier, J., Leech, K., Bockelée-Morvan, D. et al.: 1999, "The Spectrum of Comet Hale-Bopp as seen by ISO", *ESA-SP*, **427**, 137–140

Enzian, A., Cabot, H., and Klinger, J.: 1998, "Simulation of the Water and Carbon Monoxide Production Rates of Comet Hale-Bopp using a Quasi 3D Nucleus Model", *Planet. Space Sci.*, **46**, 851–858

Gunnarsson, M., Rickman, H., Festou, M.C., Winnberg, A., and Tancredi, G.: 2002, "An Extended CO Source around Comet 29P/Schwassmann-Wachmann 1", *Icarus*, in press

Irvine, W.M., Schloerb, F.P., Dickens, J.E. et al.: 1999, "The HNC/HCN Ratio in Comets", *Earth, Moon, and Planets*, **78**, 29–35

Jewitt, D., Senay M. and Matthews H.: 1996, "Observations of Carbon Monoxide in Comet Hale-Bopp", *Science*, **271**, 1110–1113

Meier, R., Eberhardt, P., Krankowsky, D. and Hodges, R.R.: 1993, "The Extended Formaldehyde Source in Comet Halley", *Astron. Astrophys.*, **277**, 677–690

Rauer, H., Helbert, J., Arpigny, C., et al.: 2002, "Optical long-term Monitoring of Comet C/1995 O1 (Hale-Bopp) at ESO", *Earth, Moon, and Planets*, *these proceedings*

Rodgers, S.D. and Charnley, S.B.: 1998, "HNC and HCN in Comets", *Astrophys. J. Lett.*, **501**, L227–L230

Stern, S.A., Colwell, W.B., Festou, M.C. et al.: 1999, "Comet Hale-Bopp (C/1995 O1) near 2.3 AU post-perihelion: Southwest Ultraviolet Imaging System Measurements of the H_2O and Dust Productions", *Astron. J.*, **118**, 1120–1125

Weaver, H.A., Feldman, P.D., A'Hearn, M.F., Arpigny, C., Brandt, J.C. and Stern, S.A.: 1999, "Post-perihelion HST Observations of Comet Hale-Bopp (C/1995 O1)", *Icarus*, **141**, 1–12

Wink J., Bockelée-Morvan D., Despois, D. et al.: 1999, "Evidences for Extended Sources and Temporal Modulations in Molecular Observations of C/1995 O1 (Hale-Bopp) at IRAM Interferometer", *Earth, Moon, and Planets*, **78**, 63