LONG TERM EVOLUTION OF THE OUTGASSING OF COMET HALE-BOPP FROM RADIO OBSERVATIONS

N. Biver,* D. Bockelée–Morvan, P. Colom, J. Crovisier, B. Germain and E. Lellouch
Observatoire de Paris-Meudon, France

J.K. Davies and W.R.F. Dent †
Joint Astronomy Centre, Hawaii, U.S.A.

R. Moreno ‡ and G. Paubert
Institut de Radio Astronomie Millimétrique, Granada, Spain

J. Wink
Institut de Radio Astronomie Millimétrique, Grenoble, France

D. Despois
Observatoire de Bordeaux, France

D.C. Lis, D. Mehringer, D. Benford, M. Gardner and T.G. Phillips
Caltech, California, U.S.A

M. Gunnarsson and H. Rickman
Uppsala Astronomiska Observatorium, Sweden

A. Winnberg, P. Bergman and L.E.B. Johansson
Onsala Space Observatory, Sweden

H. Rauer ‡
DLR, Institut für Planetenerkundung, Berlin, Germany

Abstract. C/1995 O1 (Hale-Bopp) has been observed on a regular basis since August 1995 at millimetre and submillimetre wavelengths using IRAM, JCMT, CSO and SEST radio telescopes. The production rates of eight molecular species (CO, HCN, CH_3OH, H_2CO, H_2S, CS, CH_3CN, HNC) have been monitored as a function of heliocentric distance (r_h) from 7 AU pre-perihelion to 4 AU post-perihelion. As comet Hale-Bopp approached and receded from the Sun, these species displayed different behaviours. Far from the Sun, the most volatile species were found in general relatively more abundant in the coma. In comparison to other species, HNC, H_2CO and CS showed a much steeper increase of the production rate with decreasing r_h. Less than 1.5 AU from the Sun, the relative abundances were fairly stable and approached those found in other comets near 1 AU.

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. The expansion velocity of the gaseous species, derived from the line shapes, also increased with a law close to $r_h^{-0.4}$.

Key words: Comets, C/1995 O1 (Hale-Bopp), Radio observations, Molecules

* IfA, University of Hawaii, U.S.A.
† Royal Observatory, Edinburgh, U.K.
‡ Observatoire de Paris-Meudon, France

1. Introduction

The exceptional comet C/1995 O1 (Hale-Bopp) has provided us with an unprecedented opportunity to draw the link between distant activity of a comet and its outgassing close to the Sun. We report here on the investigation of the behaviour of 8 different molecular species, observed at millimetre to submillimetre wavelengths, as a function of heliocentric distance ($r_h = 0.9$ to 6.7 AU).

2. Observations

Comet Hale-Bopp has been observed on a regular basis since September 1995, with IRAM radio telescopes (30-m and 4 to 5 15-m antennas used in single dish mode), JCMT and CSO submillimetre telescopes atop Mauna Kea, Hawaii, and observations are still in progress at SEST in Chile. Most observations were conducted in beam switching mode or using frequency switching. Updated orbital elements provided by the CBAT, D.K. Yeomans (JPL) or P. Rocher (BdL) were used for comet tracking and for backward computation of ephemeris errors. In addition, coarse mapping and direct checks of the pointing were performed on the most intense HCN lines at CSO to trace back and minimize pointing offsets. Half-power beam widths ranged from 10" to 55". 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). In addition, early investigation of the evolution of CO and CH_3OH production rates have been presented by Womack et al. (1997) and evolution of sulphur species by Woodney et al. (1998). As of January 1998, CO, HCN, CH_3OH and H_2S are still being observed while other species have fallen below detection limit. A detailed list of the observed lines and observing periods of these 8 molecules is given in Table I.

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 observations of several lines of a given species can help to constrain these values. CH_3OH (304/307 GHz), CH_3OH (157 GHz), CH_3OH (252 GHz) and CO ($J = 1$–0, 2–1, 3–2, 4–3) series of lines are of particular interest since their rotational temperature is very close to the kinetic temperature of the inner coma, unlike the CH_3OH (97 GHz) and

Table I. Observed lines

Species	Observing interval Dates	r_h range [AU]	Main frequencies observed [GHz]
CO	Sep.95 – Jan.98	6.6 – 0.9 – 4.2	115.3, 230.5, 345.8, 461.0
CH_3OH	Mar.96 – Jan.98	4.9 – 0.9 – 4.2	97, 145, 157, 242, 252, 304/307[1]
HCN	May.96 – Jan.98	4.4 – 0.9 – 4.2	88.6, 265.9, 354.5
H_2S	Jun.96 – Jan.98	4.1 – 0.9 – 4.2	168.8, 216.7
H_2CO	Jun.96 – Oct.97	4.1 – 0.9 – 3.2	140.8, 145.6, 218[2], 225.7, 351.8
CS	Jun.96 – Dec.97	4.1 – 0.9 – 3.9	98.0, 147.0, 244.9, 342.9
CH_3CN	Aug.96 – Aug.97	3.4 – 0.9 – 2.6	92, 147, 221, 239[3]
HNC	Nov.96 – Aug.97	2.4 – 0.9 – 2.2	90.7, 272.0, 362.6

[1] Main groups of lines, 69 different lines in total have been observed.
[2] 3 lines at 218.2, 218.4 and 218.7 GHz.
[3] Series of 4 to 6 lines.

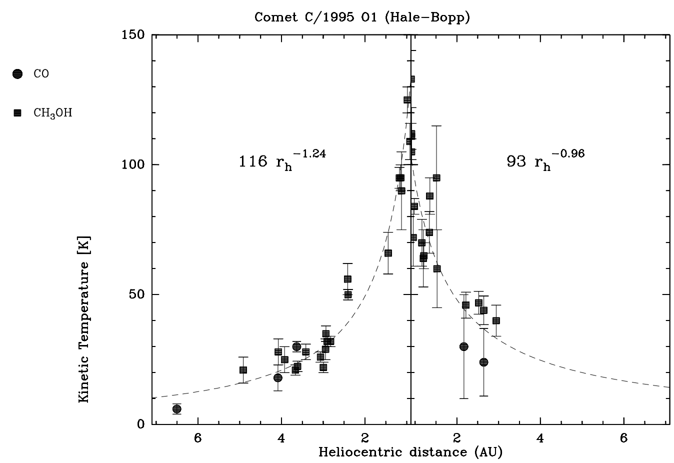

Figure 1. Evolution of the gas kinetic temperature in comet Hale-Bopp as measured from CO and CH_3OH lines with fitted power laws (dashed lines). Left: pre-perihelion data; right: post-perihelion data.

CH_3OH (145 GHz) lines (Bockelée-Morvan et al. 1994). High energy level lines were also detected and used to constrain the kinetic temperature close to perihelion. Fig. 1 shows the evolution of the kinetic temperature from 6.5 AU to perihelion and to 3.6 AU as the comet receded from the Sun. Average of pre and post-perihelion data gives $T = 103\ (\pm 7)\ r_h^{-1.10(\pm 0.08)}$ K.

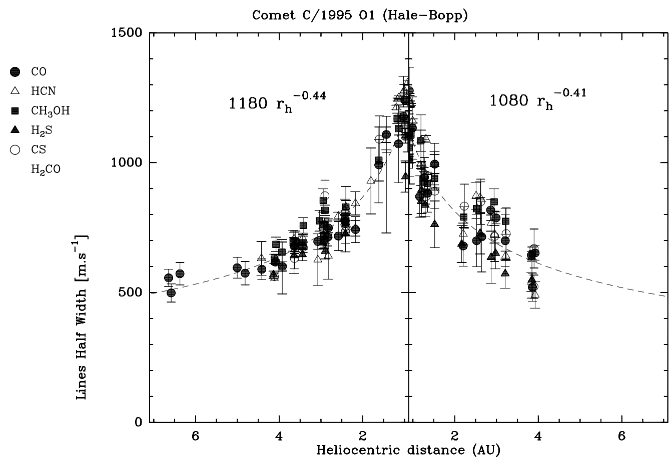

Figure 2. Velocity at half-maximum on the blue wing of the lines, which provides an estimate of the gas expansion velocity in comet Hale-Bopp. Fitted power laws are superimposed.

The line shapes of most species have been used to derive an estimate of the gas outflow velocity (v_{exp}). Given the asymmetric profiles of the lines and small phase angle ($< 49°$) a reasonable assumption that outgassing took place at least on the Earth-facing side led us to take the velocity at half-maximum of the lines on the blueshifted side as an estimate of the expansion velocity. Evolution of expansion velocity is plotted in Fig. 2, as a function of heliocentric distance. Average of pre and post-perihelion data yields $v_{exp} = 1.120\ (\pm 0.014)\ r_h^{-0.41(\pm 0.01)}$ km s^{-1}. The value we actually used to derive production rates is reduced by 10%, to take into account additional thermal broadening. This led to expansion velocities on the order of 1.05 km s^{-1} at perihelion, and 0.5 km s^{-1} at 6 AU, which is the value measured in another distant comet, 29P/Schwassmann-Wachmann 1 (Crovisier et al. 1995).

4. Production rates

The models for converting line intensities into production rates use the previously determined temperatures and expansion velocities, with a spherical 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). Life-times are taken from Crovisier (1994), and CS is assumed to be produced by CS_2 with a life-time of 10^5 s at $r_h = 1$ AU. H_2CO is also 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. 1998), as well as found in earlier comets (Colom et al. 1992; Meier et al. 1993). Its parent equivalent life-time is taken to 10^4 s. A more accurate modelling, with outgassing in a restricted cone fitting the observed line shifts, would increase production rates by 10 to 15% at most, mainly for observations between 4.5 and 2.5 AU inbound.

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

CO is the most volatile species and showed a moderate increase of its production rate at large heliocentric distances inbound (proportional to $r_h^{-2.2}$ at $r_h > 3$ AU), as well as pre-perihelion in average ($r_h^{-1.9}$) and after perihelion ($r_h^{-2.1}$). 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 Hale-Bopp's CO production (Enzian and Klinger 1998).

CH_3OH, HCN, CH_3CN and H_2S are less volatile species of lower abundance, but still overabundant in comparison to water at large heliocentric distances. The fewer data points for H_2S and CH_3CN do not enable us to discriminate a much different behaviour. Beyond 3 AU, inbound as well as outbound, all these species displayed behaviours similar to CO, though with slightly steeper variations. For CH_3OH and HCN, first upper limits obtained at 6.6 AU suggest that between 6.6 and 4.2 AU slopes may have been steeper than −4. Between 1.6 and 3 AU, inbound and outbound, the CH_3OH/HCN ratio was 50% higher than at other heliocentric distances.

CS (tracing CS_2), H_2CO and HNC production rates displayed a much steeper evolution with heliocentric distance, though these species are expected to be as volatile as the previous ones. Beyond 1.5 AU, the H_2CO/HCN, CS/HCN and HNC/HCN ratios increased with decreasing r_h with slopes of −2.1, −1.3 and −2.5, respectively. This questions the nuclear origin of these species and the way they are produced in the coma. An answer has been provided for HNC by Irvine et al. (1998) and Rodgers and Charnley (1998), involving creation from HCN through chemical reactions. The case for H_2CO suggests that its parent may be much less volatile than H_2CO itself.

Below 1.5 AU from the Sun, all species showed a dramatic increase of their production rates with decreasing heliocentric distance, exhibiting similar slopes on the order of −4.5 pre-perihelion and −3.4 post-perihelion.

Acknowledgements

We are grateful to the IRAM, JCMT, CSO and SEST staff for scheduling these long-term projects and assistance during the observations. N. Biver is currently supported by a JCMT post-doctoral fellowship.

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

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

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.: 1998, "Observations of the OH radical in Comet Hale-Bopp with the Nançay radio telescope", *these proceedings*

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

Enzian, A. and Klinger, J.: 1998, "Simulation of the water and carbon monoxide of comet Hale-Bopp using a quasi 3D nucleus model", *Planet. Space Sci.*, *in press*

Irvine, W.M., Schloerb, F.P., Dickens, J.E. et al.: 1998, "The HNC/HCN ratio in comets", *these proceedings*

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

Rodgers, S.D. and Charnley, S.B.: 1998, "HNC and HCN in Comets", *Astrophys. J. Lett.*, *in press*

Wink J., Bockelée-Morvan D., Despois, D. et al.: 1998, "Evidences for extended sources and temporal modulations in molecular observations of C/1995 O1 (Hale-Bopp) at IRAM interferometer", *these proceedings*

Womack, M., Festou, M.C. and Stern, S.A.: 1997, "The heliocentric evolution of key species in the distantly-active comet C/1995 O1 (Hale-Bopp)", *Astron. J.*, **114**, 2789–2795

Woodney, L.M., A'Hearn, M.F., McMullin, J. and Samarasinha, N.: 1998, "Sulfur chemistry at millimeter wavelengths in C/Hale-Bopp", *these proceedings*

Address for correspondence: Nicolas Biver, IfA, 2680 Woodlawn Dr., Honolulu, HI 96822, USA
E-mail: biver@galileo.ifa.hawaii.edu

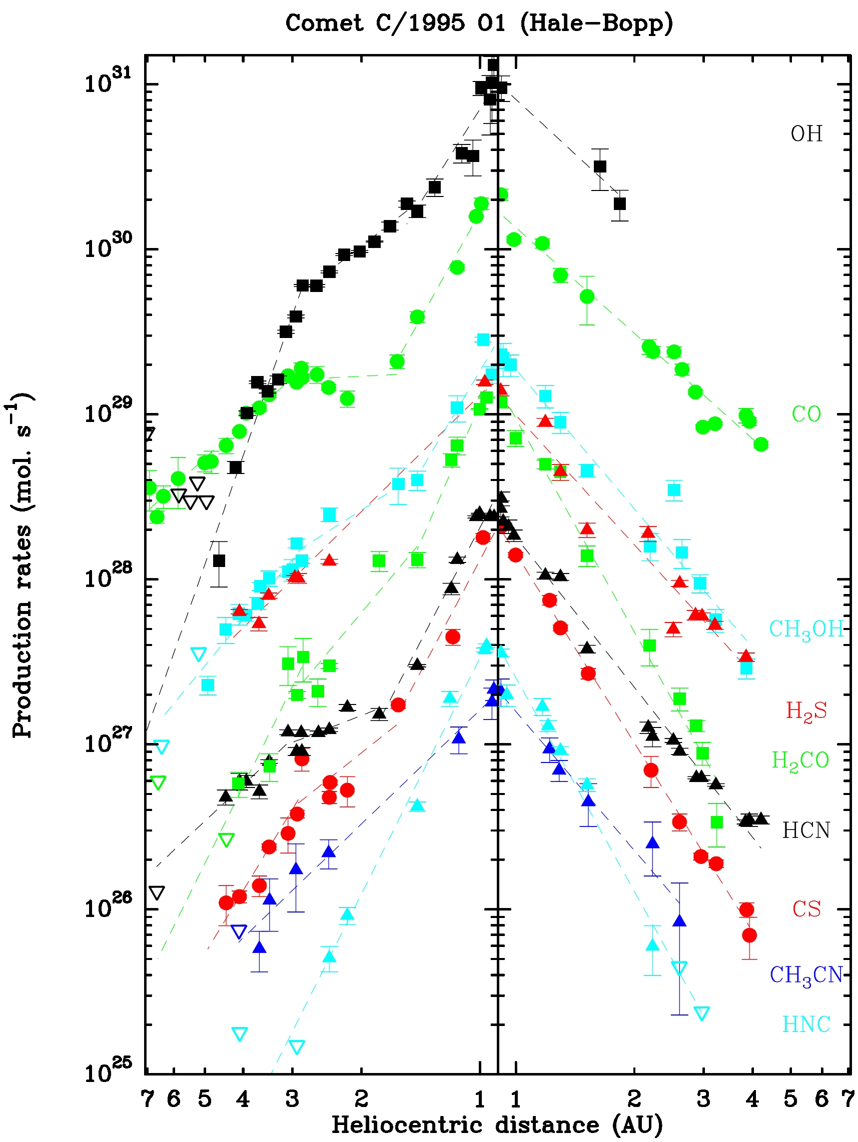

Figure 3. Evolution of production rates with heliocentric distance and fitted power laws (dashed lines). OH measurements are from Colom et al. (1998). Left: pre-perihelion data; right: post-perihelion data.