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

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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

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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 sulfur 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) and CH_3OH (252 GHz), CO (J = 1–0, 2–1, 3–2, 4–3) series of lines are of particular interest since their rotational temperature is very close

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.

to the kinetic temperature of the inner coma, unlike the CH_3OH (97 GHz) and CH_3OH (145 GHz) lines Bockelée-Morvan et al.. 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.

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, 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 leads 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..

4. Production rates

The models for converting line intensities into production rates use the previously determined temperatures and expansion velocities, with

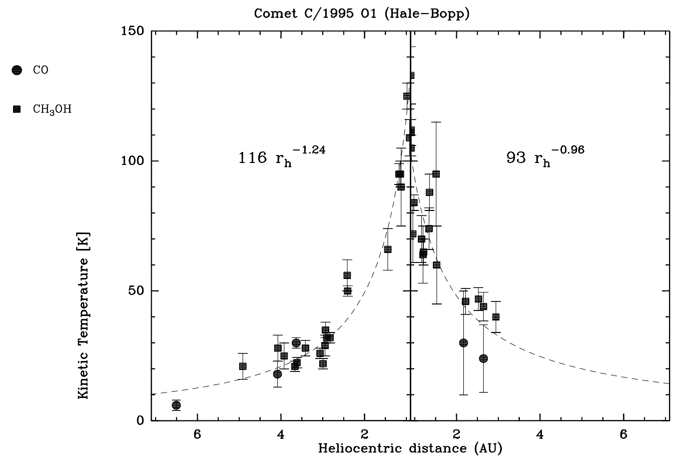

Figure 1. Evolution of the gas kinetic temperature in comet Hale-Bopp as measured from CO and CH_3OH lines with fitted power laws (dashed lines). Left: pre-perihelion data; right: post-perihelion data

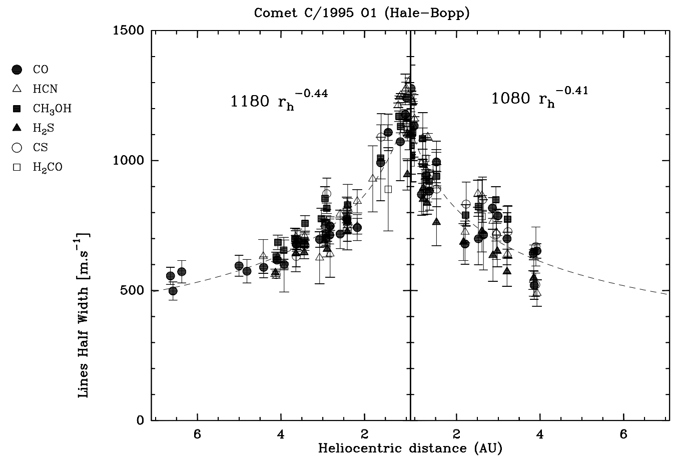

Figure 2. Velocity at half-maximum on the blue wing of the lines, which provides an estimate of the gas expansion velocity in comet Hale-Bopp. Fitted power laws are superimposed.

a spherical Haser density distribution. In addition, radiative decay and infra-red or ultra-violet pumping by solar radiation are taken into account for all molecules Biver et al. (1997). Life-times were 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 center and offset positions and from interferometric maps Wink et al. (1998), and 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 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 et al. 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, behaviours are similar to CO, with slightly steeper variations, inbound as well as outbound. 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.

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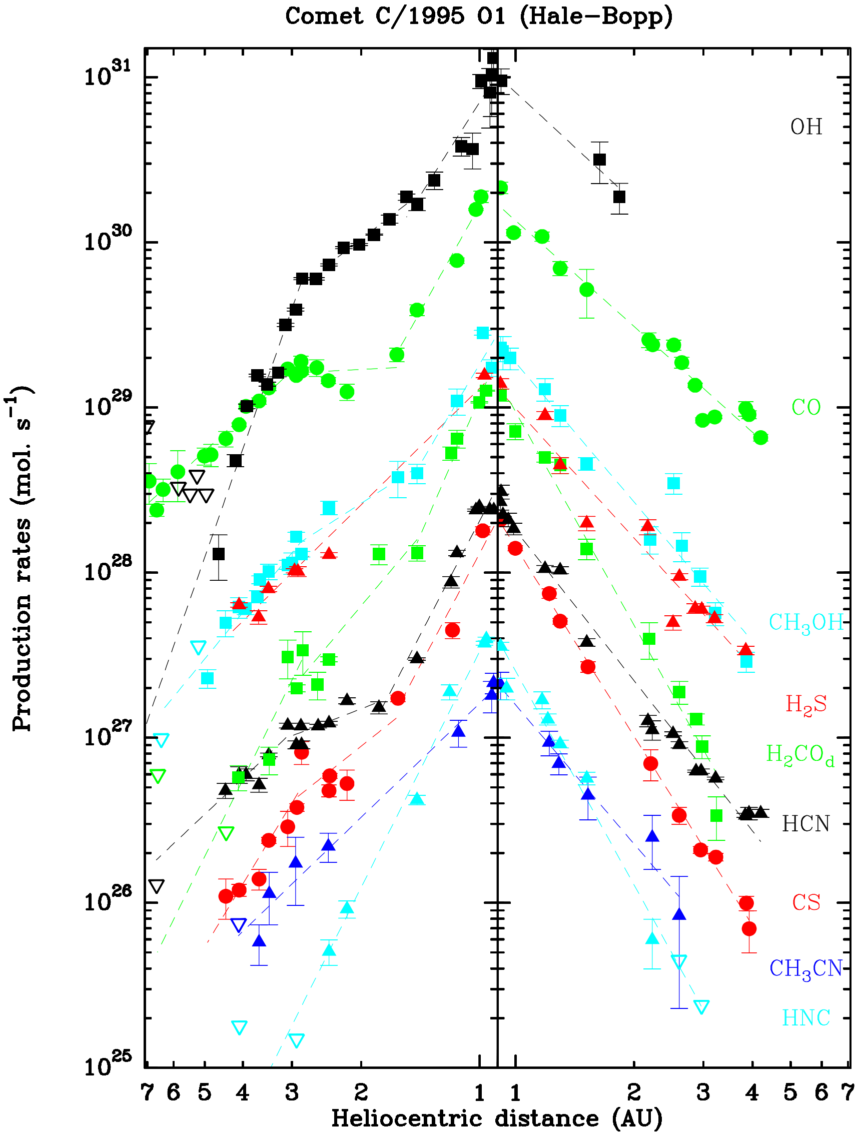

Figure 3. Evolution of production rate with heliocentric distance and fitted power laws (dashed lines). OH measurements are from Colom et al. (1998). Left: pre-perihelion data; right: post-perihelion data