

Photometric Behavior of Comet Hale-Bopp (C/1995 O1) Before Perihelion

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Narrowband photometric observations of comet Hale-Bopp (C/1995 O1) between 25 July 1995 and 15 February 1997 indicated gas and dust production rates of 20 and 100 times greater, respectively, than observed at the same heliocentric distances for comet P/Halley in 1985. Hale-Bopp produced dust at a rate greater than has been observed for any other comet at any distance since at least 1977. On the basis of the observed production rate of the hydroxyl molecule, the calculated minimum effective diameter of Hale-Bopp's nucleus is 17 kilometers, but the actual diameter of the nucleus is likely to be at least two to three times larger. The chemical composition of Hale-Bopp is consistent with that of other long-period comets originating from the Oort Cloud.

The July 1995 discovery of a comet that had already reached 11th magnitude while it was still at a heliocentric distance, r_h , of 7 astronomical units (AU) implied that the long drought of bright comets might soon end (1, 2). The realization that Hale-Bopp would reach perihelion inside Earth's orbit improved prospects further that it might become the comet of the decade (3). Finally, the confirmation that Hale-Bopp is not dynamically new, but rather made previous encounters with the sun (4), implied that Hale-Bopp was unlikely to fizzle as did comet Kohoutek (1973 XII). Analyses of brightness variations with r_h (5–7) have shown that comets making their first close passage to the sun—as was the case for Kohoutek—brighten much less as they approach the sun than do other comets, presumably due to the presence of supervolatiles. The supervolatiles, requiring less solar radiation to vaporize than the ever present H_2O or CO, release much more gas and dust at large values of r_h than is typical. As the supervolatiles are depleted, the high rate of gas and dust production cannot be maintained, resulting in a comet that does not brighten appreciably as it nears the sun, unlike “old” comets such as Hale-Bopp.

Because of Hale-Bopp's unusually high level of activity and early discovery, it was possible to measure production rates of the various species over an unprecedented range of r_h (7). For comparison, even comet P/Halley was at $r_h < 3$ AU before it was bright enough for photoelectric narrowband measurements. Most other comets in our program (7) that were observed at $r_h > 3$ AU also reached perihelion at $r_h > 2$ AU.

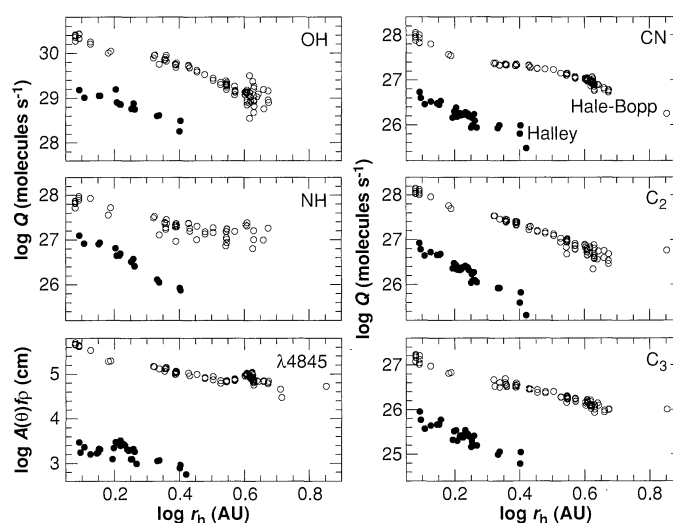
Consequently, it has been difficult to investigate the critical 3- to 5-AU region within which H_2O is expected to replace CO as the dominant volatile. Indeed, CO was detected within 2 months of Hale-Bopp's discovery (8, 9). By measuring the abundance of H_2O , the various minor gas species, and the dust in the coma through this critical regime and on into perihelion, we hoped to obtain a better understanding of the physical and chemical processes taking place on the surface of a steadily warming nucleus.

Here we present photometric results beginning on 25 July 1995 (r_h of 7.14 AU, only 2 days after discovery), continuing from 25 February to 5 December 1996 (corresponding to a range in r_h of 5.20 to 2.09 AU), and concluding with our most recent observations from 17 January to 15 February 1997 (1.55 to 1.20 AU). Data were recorded on 48 nights with the 42-inch (1.1-m) Hall Telescope and the 31-

inch (0.8-m) Telescope at Lowell Observatory. A conventional, single-channel photoelectric photometer equipped with pulse-counting electronics was used for the observations. Narrowband filters—most from the International Halley Watch filter set—isolated emission bands of OH, CN, C_2 , C_3 , and NH, along with continuum regions centered at 3650 and 4845 Å. Photometric reductions and the subsequent computation of molecular abundances and Haser-model production rates, Q , as well as the computation of $A(\theta)f\rho$ —a proxy for dust production—followed our standard procedures and model parameters (7). The product of $A(\theta)$ (the Bond albedo at the particular phase angle of observation), f (the filling factor of the grains within the field of view of the aperture), and ρ (the projected radius of the aperture), $A(\theta)f\rho$ is an aperture-independent quantity for a comet with a canonical spatial distribution of dust. Some emission measurements were noise-dominated due to the weakness of the corresponding emission features at large r_h , coupled with an unusually strong underlying continuum and an occasionally bright sky due to moonlight. Therefore, values of Q are given here only when the emission component was $>5\%$ of the gross (continuum plus emission plus sky) signal (Fig. 1). We also present only the 4845 Å continuum measurements of the dust production, because the 3650 Å values are consistent with the longer wavelength results but have poorer signal-to-noise ratios due to the lower solar flux at ultraviolet wavelengths.

The $A(\theta)f\rho$ of 50,000 cm measured from the July 1995 observation is already greater

Fig. 1. Production rates as a function of heliocentric distance for Hale-Bopp (open symbols). Observations span a range from 7.1 AU in July 1995 (far right of panels) to 1.2 AU in February 1997. For comparison, production rates observed in Halley (closed symbols) in 1985 before perihelion are also presented (13). The gas production (Q) for Hale-Bopp is ~ 20 -fold greater than for Halley at any given distance, whereas the dust production [$A(\theta)f\rho$] is more than 100-fold greater. The production rate of dust in Hale-Bopp is higher than that measured for any comet in our database (7). In general, uncertainties in the measurements for Hale-Bopp can be estimated from the scatter in the individual data points.



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than that measured for any comet in our database (7) at any distance. Although each of the carbon-bearing species was nominally detected in 1995, only the CN detection can be considered reliable, due to the relatively high contrast of the narrow CN emission band with the underlying continuum. Our CN production rate of $1.8 \pm 0.6 \times 10^{26}$ molecules s^{-1} is higher than other reported values from observations made 1 month later (10, 11). The apparent discrepancies in Q_{CN} are mostly due to the use of different g -factors (fluorescence efficiencies) and models. We have recalculated production rates on the basis of information given in (10) and (11) using our standard model, yielding values of Q_{CN} of $1.2 \pm 0.6 \times 10^{26}$ and $1.2 \pm 0.2 \times 10^{26}$ molecules s^{-1} for (10) and (11), respectively, which agree with our Q_{CN} within the errors. An observation from mid-October 1995 ($r_h = 6.5$ AU) also gives a similar value of $1.2 \pm 0.3 \times 10^{26}$ molecules s^{-1} with our same model parameters (12). The much broader C_2 and C_3 bands have lower contrast to the continuum than does the CN band, and their detections must be considered marginal, whereas OH and NH were not detected in 1995.

Hale-Bopp's dust production rate was more than two orders of magnitude greater than Halley's at a comparable distance (13). In addition, the dust-to-gas ratio, $\log A(\theta)f\rho/Q_{OH} \approx -24.7$ cm s molecules $^{-1}$, is at the high end of the range of values, -24.4 to -26.5 cm s molecules $^{-1}$, displayed by other comets (7). By any measurement, Hale-Bopp is an extraordinarily dusty comet. In comparison, the overall Q_{gas} of Hale-Bopp is about 20 times greater than for Halley. In general, Q_{gas} depends on r_h more than Q_{dust} , but the differences among the various gas species and the dust in this regard are less extreme at $r_h \leq 2.5$

AU. This behavior might imply that the difference in the r_h dependencies at larger distances could be due to systematic effects in the modeling caused by inaccurate scale lengths for the gas species, rather than to inherently different physical processes. Given that the scale lengths were empirically determined from observations of spatial profiles recorded in other comets between 0.7 and 1.5 AU (7, 14) and then scaled by r_h^2 , this explanation is certainly feasible. From about 2.5 to 1.6 AU, all species exhibit relatively low r_h dependencies—with power-law exponents ranging from -1 to -2 . However, in our last month of observations ($r_h < 1.6$ AU), Hale-Bopp displayed increased r_h dependencies for all of the gas species as well as the dust, making it difficult to predict what the peak Q_{H_2O} or the visible brightness will be at perihelion ($r_h = 0.91$ AU).

In spite of the apparent large scatter in the derived Q for each gas species in June 1996 ($\log r_h = 0.60$ to 0.64), we see little evidence for short-term variability in Q in 1996, either during a single night or from night to night. Rather, the variation in values of Q (Fig. 1) primarily results from the use of a number of different photometric entrance apertures each night. Such an explanation is consistent with inaccurate model scale lengths and the resulting derived spatial distribution of the gas within the comet's coma at large r_h . However, a clear dependence of Q on aperture size was also evident in February 1997 at small r_h , where the model scale lengths are expected to be good, implying another physical process might have been at work. Numerous imaging investigations during 1996 (15, 16) showed morphological features—a large overall spatial asymmetry and >5 linear dust jets radiating from the nucleus—that changed only on a time

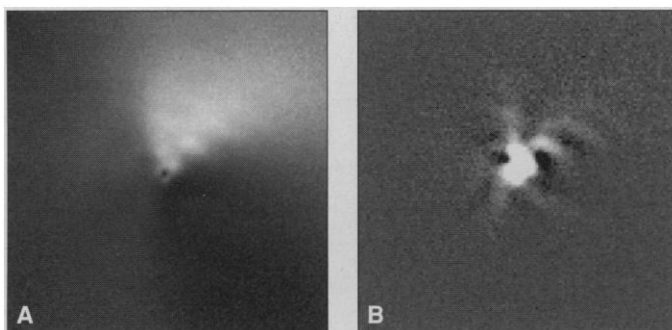
scale of many weeks to months, indicating that the rotation period might be many months in duration. An alternative explanation for the lack of variation in the morphological features, however, indicated that the morphology was insensitive to the comet's rotation rate (17). Recent imaging observations (16, 18) have revealed significant changes in the gross morphology on a time scale of weeks and, more importantly, regularly spaced brightness variations within the dust jets (Fig. 2), consistent with a fast-rotating (<1 day) nucleus. Rapid, periodic variations in the release of material from the nucleus can readily manifest themselves as systematic variations with aperture size in the derived production rates, as previously observed in Halley (19). Although we did not detect brightness variations during individual nights in June 1996, this was apparently due to the large projected field-of-view of our photometer. As a result, material from several rotational cycles was contained within our entrance aperture at all times, thereby masking any rapid rotational modulation.

The total size of the active area on Hale-Bopp's nucleus was estimated from the OH observations (Fig. 1) at $r_h < 3$ AU. Restricting the calculations to small r_h minimized systematic effects caused by possible inaccuracies in the model scale lengths. Combining a H_2O vaporization model with the conversion from OH production to H_2O production (7, 20), we obtained a minimum active area of 930 km 2 and a minimum effective diameter of the nucleus of 17 km. However, it is evident from the prominent jets present in Hale-Bopp's coma (Fig. 2) that much of the activity emanates from discrete regions on the nucleus. Therefore, the actual diameter of this comet's nucleus is likely to be at least two to three times larger than our calculated minimum diameter.

Finally, the relative Q 's among the observed gas species, and therefore their relative abundances, can be compared with that of other comets (7). We used Q 's for Hale-Bopp that were obtained only at $r_h < 3$ AU, because the relative abundances for other comets were restricted to $r_h < 3$ AU. Nearly all long-period comets, which are believed to originate in the Oort Cloud, have a "typical" composition, with near equal production rates of CN and C_2 (7). About 50% of short-period, low-inclination comets believed to originate from the Kuiper Belt are also typical in their composition, but the remaining Kuiper Belt objects are depleted in carbon-chain molecules (C_2 and C_3). Our observations of Hale-Bopp show that its composition is "typical," which is consistent with this long-period, high-inclination comet originating in the Oort Cloud.

Fig. 2. Charge-coupled device image of Hale-Bopp obtained with the Hall 42-inch Telescope on 14 February 1997. A narrowband continuum filter centered at 7128 Å was used, resulting in an image of the light reflected from dust particles. After bias subtraction and flat-fielding, the image was processed (A)

by removal of a canonical $1/\rho$ fall-off, where ρ is the projected distance from the nucleus. This resulted in an image dominated by deviations from the canonical case. The regularly spaced brightness variations within the upper-right quadrant, apparently due to periodic changes in dust production caused by active regions on the surface, turn on and off as they rotate into and out of sunlight. The image was also processed (B) by an unsharp masking technique to enhance the spatial structures within the inner coma. Numerous dust jets and arcs are apparent that are dissimilar in appearance to the simple radial jets observed in Hale-Bopp throughout the latter half of 1996. The trimmed image is 136 arc sec or 172,000 km on a side.



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Evolution of the Outgassing of Comet Hale-Bopp (C/1995 O1) from Radio Observations

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Spectra obtained from ground-based radio telescopes show the progressive release of CO, CH₃OH, HCN, H₂O (from OH), H₂S, CS, H₂CO, CH₃CN, and HNC as comet Hale-Bopp (C/1995 O1) approached the sun from 6.9 to 1.4 astronomical units (AU). The more volatile species were relatively more abundant in the coma far from the sun, but there was no direct correlation between overabundance and volatility. Evidence for H₂O sublimation from icy grains was seen beyond 3.5 AU from the sun. The change from a CO-driven coma to an H₂O-driven coma occurred at about 3 AU. The gas outflow velocity and temperature increased as Hale-Bopp approached the sun.

Cometary nuclei are porous bodies consisting of a mixture of ices and refractory grains. Progress made in the identification of cometary volatiles shows that ices of different volatility coexist in the nucleus (1). Although H₂O is the dominant ice and controls cometary activity within 3 AU from the sun, the recent detection of CO in the distant comet P/Schwassmann-Wachmann 1 at millimeter wavelengths (2) suggested that, farther from the sun, cometary activity is

driven by the sublimation of more volatile species. Questions arise as to the physical state and sublimation mechanisms of ices and the relative roles of the various volatiles in the comet's activity. Given the existence of processes causing chemical differentiation within the nucleus, an important issue is whether the molecular abundances measured in the coma near perihelion are representative of the bulk composition of the nucleus. The discovery of Hale-Bopp at heliocentric distance $r_h = 7$ AU (3) offered us the opportunity to address these problems observationally by following the outgassing of this exceptionally bright comet over a wide range of r_h .

Hale-Bopp was observed on a regular basis between August 1995 and late January 1997 with the Nançay telescope, the Institut de Radio Astronomie Millimétrique (IRAM) 30-m telescope (4), and the James Clerk Maxwell Telescope (JCMT) (5) at

decimeter, millimeter, and submillimeter wavelengths, respectively. The OH lines at 18 cm were monitored at Nançay, and observations at IRAM and JCMT focused on rotational lines of parent molecules. The general goals of this campaign were to (i) observe the onset of outgassing of the different species, (ii) monitor their production rates as a function of r_h , and (iii) constrain the kinetic temperature and expansion velocity in the coma and their variation with r_h . Several transitions of the same molecule were observed simultaneously whenever possible to understand the excitation conditions in the coma and to infer the production rates.

Observations at IRAM started in mid-August 1995, when Hale-Bopp was at $r_h = 6.9$ AU (6). Monitoring of OH at Nançay started in December 1995, although preliminary observations had been acquired earlier (7). We detected more than 50 molecular lines, showing the progressive release of nine molecular species (CO, CH₃OH, HCN, OH, H₂S, H₂CO, CS, CH₃CN, and HNC) as the comet approached the sun (Table 1). With the exception of NH₃, OCS, HNCO, and some isotopic species, identified in comet Hyakutake (C/1996 B2) (8), all molecular species detected at radio wavelengths in previous comets were observed in Hale-Bopp at $r_h > 2.4$ AU. A number of species were also observed at other wavelengths. In particular, the first detection of the OH radical was actually obtained with the Hubble Space Telescope (9) 2 weeks before its radio detection. In addition, CO₂, CO, and H₂O were detected at infrared wavelengths by the Infrared Satellite Observatory (10).

Most of the lines in our spectra were blueshifted with respect to the geocentric radial velocity of the comet (Fig. 1). Because the phase angle was always $<20^\circ$, this velocity shift is indicative of anisotropic outgassing with preferred outflow from the sunward side of the nucleus. Coarse mapping of the HCN lines, performed from August to October 1996, showed enhanced outgassing $\sim 45^\circ$ N from the sun position angle. Beyond $r_h = 3.5$ AU, the OH lines were less blueshifted than the CO lines (Fig. 2A). Although to a lesser extent, the same behavior is observed at $r_h > 4$ AU for the CH₃OH lines. This behavior indicates that some molecular species, such as H₂O and CH₃OH, were partly sublimating from icy grains when observed far from the sun, in contrast to the more volatile CO molecule outgassed mainly from the nucleus. Icy grains of H₂O were detected through their infrared spectral signature at 1.5 and 2.05 μm when Hale-Bopp was at $r_h = 6.8$ AU (11). The low Doppler shifts of the OH and CH₃OH lines (that is, low bulk velocity of

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