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29. For dust having an average radius  $a$  (in micrometers), density  $d$  (in grams per cubic centimeter), geometric albedo  $A_p$ , and flowing outward from the nucleus with velocity  $v_{dust}$  (in kilometers per second), the dust mass production rate,  $Q_{dust}$  (in kilograms per second) is given by:  $Q_{dust} = (0.67) a d v_{dust} Afp / A_p$  where  $Afp$  is in meters. We calculated  $Q_{dust}$  using  $v_{dust} = 0.13 r_h^{-0.5} (30)$ ,  $a = 10$ ,  $d = 1$ , and  $A_p = 0.04$  (Table 1 and Fig. 4).
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33. A spectrum ending at 14:05 universal time (UT) on 23 September 1996 had essentially the same continuum flux as other spectra that were taken between 10:30 and 14:05 UT. (The spectra were not continuously recorded during this latter period because the HST periodically passes behind the Earth, at which times the comet was not visible from HST. The HST orbital period is 96 min, and observations are generally limited to a duration of ~30 min each orbit.) Following a gap in our coverage due to Earth occultation, a 2-min spectrum starting at 13:41 UT had a continuum level that was 3.4 times larger than that recorded during the earlier times. In addition, three subsequent 2-min spectra showed the continuum intensity monotonically increasing at the rate of ~1.2% min<sup>-1</sup>.
34. We ruled out pointing error as the source of the observed temporal variation by verifying that the flux measured in spectra taken immediately before the outburst was essentially identical to that measured during observations spanning up to ~6.5 hours earlier. A solar-type star entering the aperture and having a visual magnitude of ~11.5 could have produced the observed increase in the continuum, but no such object was present in the cometary field. Furthermore, another object entering the aperture would not explain the observed increase in CS emission. During the outburst, the spatial distribution of the continuum became markedly more peaked towards the nucleus, which is consistent with a dust outburst originating at the nucleus of the comet.
35. For spherically symmetric outflow of dust from the nucleus with velocity  $v$ , it is easy to show that the total number of grains,  $n_g$ , in a circular aperture of radius  $\rho$  is given by  $n_g = (\pi/2) Q_d \rho / v$ , where  $Q_d$  is the dust production rate (in particles per second) under steady-state conditions. The number of extra dust grains,  $n_o$ , created during an outburst of duration  $t$  is given by  $n_o = Q_o t$ , where  $Q_o$  is the extra production rate above the quiescent value averaged over the duration of the outburst. Since  $n_o/n_g = 2.4$ ,  $\rho = 2570$  km, and  $t = 4635$  s for our observations, the ratio of these two production rates is given by  $2.1/v$  when  $v$  is in kilometers per second. Using our adopted value for  $v$  (0.076 km s<sup>-1</sup>) yields a  $Q$  ratio of 28. In cometary work it is usually assumed that the dust velocity is given by  $v \sim 0.5 r_h^{-0.5}$  [N. T. Bobrovnikov, *Astron. J.* **59**, 357 (1954)], which gives a  $Q$  ratio of 7 and implies that the total dust production rate averaged over the outburst was eight times the quiescent value.
36. Assuming that all of the molecules produced during the outburst are contained in the observing aperture, the number of daughter molecules,  $n_d$ , at time  $t$  following the outburst is related to the number of parent molecules,  $n_p$ , produced during the outburst by  $n_d = n_p (1 - e^{-t/\tau})$ , where  $\tau$  is the parent lifetime. Using our adopted lifetimes for CS<sub>2</sub> and H<sub>2</sub>O, and an outburst duration of 4635 s, we see that the increase in the number of CS molecules should be ~64% of the increase in the number of CS<sub>2</sub> molecules, while the number of extra OH molecules should increase by less than 1% of the increase in H<sub>2</sub>O molecules.
37. Support for this work was provided by NASA through grant numbers GO-05844 and GO-06663 from the Space Telescope Science Institute (STScI), which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. C. Arpigny gratefully acknowledges financial support by the Belgian Fonds National de la Recherche Scientifique. We thank A. Lubenow and A. Storrs of the STScI for expertly planning the HST observations of Hale-Bopp. We also express our gratitude to W. Wamsteker and H. Aendernach for their strong support of the IUE Hale-Bopp program.

28 January 1997; accepted 3 March 1997

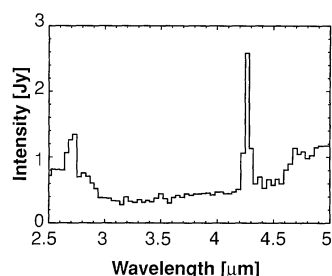
## The Spectrum of Comet Hale-Bopp (C/1995 O1) Observed with the Infrared Space Observatory at 2.9 Astronomical Units from the Sun

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Comet Hale-Bopp (C/1995 O1) was observed at wavelengths from 2.4 to 195 micrometers with the Infrared Space Observatory when the comet was about 2.9 astronomical units (AU) from the sun. The main observed volatiles that sublimated from the nucleus ices were water, carbon monoxide, and carbon dioxide in a ratio (by number) of 10:6:2. These species are also the main observed constituents of ices in dense interstellar molecular clouds; this observation strengthens the links between cometary and interstellar material. Several broad emission features observed in the 7- to 45-micrometer region suggest the presence of silicates, particularly magnesium-rich crystalline olivine. These features are similar to those observed in the dust envelopes of Vega-type stars.

The infrared (IR) wavelength region is useful for investigating comets because (i) comets are cold and the thermal emission of the nucleus and dusty atmosphere peaks at IR wavelengths and (ii) the volatile molecular species, sublimated from cometary nucleus

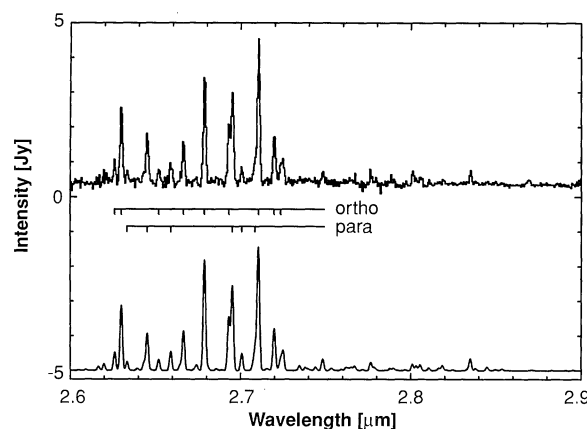
ices, can be identified through their fundamental bands of vibration, which are seen in fluorescence excited by solar radiation. IR observations of comets (1–3) from the ground are limited to a few atmospheric windows. IR spectra of comets above Earth's atmosphere



**Fig. 1.** The 2.5- to 5- $\mu\text{m}$  spectrum of Hale-Bopp observed with PHT-S on 27 September 1996. The aperture is 24 arc sec  $\times$  24 arc sec and the spectral resolution is  $\lambda/\delta\lambda \sim 90$ . Conspicuous are the bands of  $\text{H}_2\text{O}$  at 2.7  $\mu\text{m}$ ,  $\text{CO}_2$  at 4.25  $\mu\text{m}$ , and CO at 4.65  $\mu\text{m}$ .

have been observed for comet Halley, from the VEGA space probes, and from the Kuiper Airborne Observatory (4–7), but they were limited in spectral coverage, resolution, or both. Hale-Bopp, an intrinsically bright long-period comet ( $P \sim 2500$  years) that will reach perihelion at 0.91 AU on 1 April 1997, provides a rare opportunity to measure the whole IR spectrum of a comet with good spectral resolution and sensitivity, by use of the Earth-orbiting Infrared Space Observatory (ISO).

Our observations (8) were performed with the grating spectrometer of the photometer (PHT-S, wavelengths of 2.5 to 5 and 6 to 12  $\mu\text{m}$ ), the short-wavelength spectrometer (SWS, 2.4 to 45  $\mu\text{m}$ ), and the long-wavelength spectrometer (LWS, 45 to 195  $\mu\text{m}$ ) on board ISO (9). The 2.5- to 5- $\mu\text{m}$  spectral region covers the most intense fundamental vibrational bands of cometary volatiles which are emitted through fluorescence (1). This region was observed at low resolution with PHT-S. In April, only the  $\nu_3$  band of  $\text{CO}_2$  at 4.25  $\mu\text{m}$  was detected (10). On 27 September and 6 October, we detected the  $\nu_3$  band of  $\text{CO}_2$  with a high signal-to-noise ratio (SNR), the  $\text{H}_2\text{O}$  band at 2.7  $\mu\text{m}$ , and the CO  $\nu(1-0)$  band (Fig. 1) (11). These bands were also observed at higher spectral resolution with the SWS (12). The CO and  $\text{CO}_2$  bands were seen with a lower SNR compared to the PHT-S spectra due to the limited sensitivity of the SWS detectors at these wavelengths. The 3.2- to 3.6- $\mu\text{m}$  emission, which is a major feature of comets observed at  $\sim 1$  AU and is attributed to methanol ( $\text{CH}_3\text{OH}$ ), ethane ( $\text{C}_2\text{H}_6$ ), and other unidentified species (3, 13), was only detected in the SWS spectra.



**Fig. 2.** (Top) The 2.6- to 2.9- $\mu\text{m}$  spectrum of Hale-Bopp observed with the SWS, an average of the 27 September and 6 October 1996 data. The aperture is 14 arc sec  $\times$  20 arc sec and the spectral resolution is  $\lambda/\delta\lambda \sim 1500$ . (Bottom) The synthetic fluorescence spectrum of water for  $Q_{\text{H}_2\text{O}} = 3.6 \times 10^{29} \text{ s}^{-1}$ ,  $T_{\text{rot}} = 28.5 \text{ K}$ , and OPR = 2.45, which is the best fit to the data. All the observed lines are due to water, except the line at 2.869  $\mu\text{m}$  which is identified to the OH  $\nu(1-0) P_1$  (5/2) transition. The *ortho* and *para* lines of the  $\nu_3$  band of water are tagged.

The gas production rates  $Q$  for  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and CO were evaluated assuming resonant fluorescence excited by the sun (Table 1) (1, 14). We assumed optically thin gas flowing isotropically at constant velocity [ $0.5 \text{ km s}^{-1}$  in April and  $0.7 \text{ km s}^{-1}$  in September (15)] and standard photodissociation lifetimes (16). These parameters are fairly well known, and the principal source of error in the gas production rates is probably the  $\sim 30\%$  uncertainty in the flux calibration.

Other determinations of the production rates of CO and  $\text{H}_2\text{O}$  (from OH) at radio wavelengths and in the ultraviolet with the Hubble Space Telescope are similar to our estimates (17). The production rates of CO and  $\text{CO}_2$  relative to  $\text{H}_2\text{O}$  at large heliocentric distances ( $r_h$ ) where Hale-Bopp was observed may not be representative of the true mixing ratios in the nucleus because of the high volatility of these species. Numerical simulations (18) have been used to evaluate this fractionation effect, which appears to be important at  $r_h = 4.6 \text{ AU}$ . At  $r_h = 2.9 \text{ AU}$ , the  $[\text{CO}]/[\text{H}_2\text{O}]$  and  $[\text{CO}_2]/[\text{H}_2\text{O}]$  measured in the coma of Hale-Bopp could be closer to the mixing ratios of the nucleus ices, but may still be an overestimate. In any case,  $\text{H}_2\text{O}$ , CO, and  $\text{CO}_2$  appear to be the main observed constituents of cometary ices. Other constituents have relative abundances of the order of a few percent, at most (15, 19). In this respect, the composition of cometary ice appears to be very similar to that of interstellar ice observed by ISO (20).

On 27 September and 6 October, specific SWS observations were dedicated to the 2.6- to 2.9- $\mu\text{m}$  spectral region, which contains bands of water ( $\nu_1$ ,  $\nu_3$ , and several hot bands), as well as the O-H stretching modes of several molecules (Fig. 2). The strong lines observed between 2.62 and 2.73  $\mu\text{m}$  belong to the  $\nu_3$   $\text{H}_2\text{O}$  band, resolved into its ro-vibrational lines. The 2.73- to 2.90- $\mu\text{m}$  region shows several weak lines. Using a fluorescence model of  $\text{H}_2\text{O}$  (14, 21), we computed a synthetic spectrum that takes into account excitation of the  $\nu_1$  and  $\nu_3$  fundamental bands and of the  $\nu_2$

+  $\nu_3 - \nu_2$ ,  $\nu_1 + \nu_3 - \nu_1$ , and  $\nu_1 + \nu_3 - \nu_3$  hot bands of  $\text{H}_2\text{O}$ . There is a good match with the observed weak features (Fig. 2). This confirms that the cometary emission around 2.8  $\mu\text{m}$ , previously found in Halley and comet Wilson (C/1986 P1) (22), is mainly due to  $\text{H}_2\text{O}$  (21). An additional line observed at 2.869  $\mu\text{m}$  corresponds to the  $\nu(1-0) P_1$  (5/2) transition of OH. The fluorescence of this line was predicted to be strong, together with the  $\nu(1-0) Q_1$  (3/2) line at 2.803  $\mu\text{m}$ , which appears in our spectrum to be blended with  $\text{H}_2\text{O}$  lines (23).

The lines of the  $\nu_3$   $\text{H}_2\text{O}$  band are observed with high SNR. Their relative intensities are sensitive to the physical conditions of cometary water. They allow us to measure the  $\text{H}_2\text{O}$  rotational temperature ( $T_{\text{rot}}$ ) and its *ortho*-to-*para* ratio (OPR), a tracer of the origin and evolution of comets (24). Using our model (14, 21), we solved by a least-square method for the production rate, the OPR and  $T_{\text{rot}}$  which give the best fit to the observed spectrum (Fig. 2). We assumed that the rotational population distributions for both *para* and *ortho* states can be described by a single  $T_{\text{rot}}$  and we took opacity effects into account (14). The

**Table 1.** Molecular production rates from PHT-S spectra. Upper limits are  $3\sigma$ . All these results are subject to a 30% uncertainty on the calibration. The band for  $\text{H}_2\text{O}$  and  $\text{CO}_2$  is  $\nu_3$  and the band for CO is  $\nu(1-0)$ . The  $g$ -factors (fluorescence efficiency, in  $\text{s}^{-1}$ ) are as follows:  $\text{H}_2\text{O}$ ,  $2.9 \times 10^{-4}$ ;  $\text{CO}_2$ ,  $2.6 \times 10^{-3}$ ; CO,  $2.6 \times 10^{-4}$ . Molec. indicates molecule.

| Molec.                                                              | Flux<br>( $\text{W m}^{-2}$ ) | $Q$<br>(Molec. $\text{s}^{-1}$ ) |
|---------------------------------------------------------------------|-------------------------------|----------------------------------|
| 27 Apr. 1996: $r_h = 4.59 \text{ AU}$ , $\Delta = 4.28 \text{ AU}$  |                               |                                  |
| $\text{H}_2\text{O}$                                                | $< 2.6 \times 10^{-15}$       | $< 1.1 \times 10^{29}$           |
| $\text{CO}_2$                                                       | $2.1 \times 10^{-15}$         | $1.3 \times 10^{28}$             |
| CO                                                                  | $< 1.2 \times 10^{-15}$       | $< 9.0 \times 10^{28}$           |
| 27 Sept. 1996: $r_h = 2.93 \text{ AU}$ , $\Delta = 2.96 \text{ AU}$ |                               |                                  |
| $\text{H}_2\text{O}$                                                | $2.0 \times 10^{-14}$         | $3.3 \times 10^{29}$             |
| $\text{CO}_2$                                                       | $2.7 \times 10^{-14}$         | $7.4 \times 10^{28}$             |
| CO                                                                  | $6.7 \times 10^{-15}$         | $2.3 \times 10^{29*}$            |

\*subject to baseline uncertainty.

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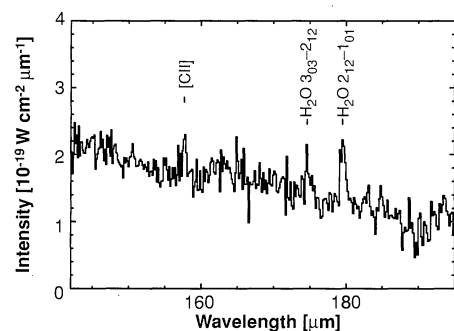
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retrieved  $T_{\text{rot}}$  is 28.5 K, in agreement with the temperatures derived from the radio lines of other species (15). The OPR is  $2.45 \pm 0.10$  and is significantly lower than the statistical equilibrium value of 3, achieved for temperatures exceeding  $\sim 60$  K. Such a value suggests that cometary  $\text{H}_2\text{O}$  molecules formed at a temperature of  $\sim 25$  K and were not subject to subsequent re-equilibration (25).

Water was also observed at  $6\text{ }\mu\text{m}$  by the SWS through the ro-vibrational lines of its  $\nu_2$  band. In addition, the far-IR LWS spectrum (Fig. 3) shows emission of the  $2_{12}\text{-}1_{01}$  rotational line of water [the  $2_{21}\text{-}2_{12}$   $\text{H}_2\text{O}$  line falls at a very close wavelength; its intensity in cometary atmospheres is expected to be much smaller, however (14)]. The  $3_{03}\text{-}2_{12}$   $\text{H}_2\text{O}$  line is also marginally present. These lines are, as predicted (1, 14), the strongest cometary lines in this spectral domain. Acting as coolers, they have an important role in the thermal balance of cometary atmospheres.

The 7- to  $45\text{-}\mu\text{m}$  region observed with the SWS on 6 October (the spectrum obtained on 27 September is almost identical) shows continuum and strong emission features at 10 to 12, 19.5, 23.5, and  $33.5\text{ }\mu\text{m}$ ; less intense features are also seen at 16 and  $27.5\text{ }\mu\text{m}$  (Fig. 4). The spectrum represents thermal emission from the dust grains in the coma. A temperature of 200 K was derived by fitting a black-body curve to the spectrum at 7.5 and 13 to  $15\text{ }\mu\text{m}$  (Fig. 4). The fitted black-body temperature is  $\sim 20\%$  higher than the calculated equilibrium black-body temperature of 162 K at  $r_h = 2.9$  AU, indicating that the thermal emission arises from particles that are small compared to the wavelength.

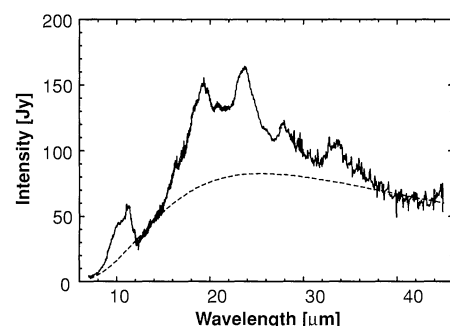
The spectral peaks may be indicative of minerals within the dust particles. The emission feature at a wavelength of 9 to  $12\text{ }\mu\text{m}$  has been observed from the ground for a number of comets at spectral resolution



**Fig. 3.** The rotational water lines observed in Hale-Bopp with the LWS on 6 October 1996. The aperture is 100 arc sec and the spectral resolution is  $\lambda/\delta\lambda \sim 200$ . The [ClII] line at  $157.7\text{ }\mu\text{m}$ , also present in the same field observed several days later, is probably due to emission originating in the background interstellar medium.

$\sim 50$  (2, 5), including Hale-Bopp (26). This band may be due to the stretching mode of Si-O in small silicate grains. Several of the comets, including Hale-Bopp, exhibit a distinct peak at  $11.3\text{ }\mu\text{m}$  superimposed on a broader emission; this peak may be attributed to crystalline olivine (2). Amorphous silicates have only broad bands around 10 and  $20\text{ }\mu\text{m}$  (27). The broad excess emission at 16 to  $26\text{ }\mu\text{m}$  in our spectrum is typical of silicates (27–30), regardless of specific mineralogy. Crystalline olivine ( $\text{Mg, Fe}$ ) $_2\text{SiO}_4$  has additional bands at 16.5, 19.8, 24.0, 27.6, and  $33.9\text{ }\mu\text{m}$  (28, 29). Crystalline pyroxene ( $\text{Mg, Fe, Ca}$ ) $\text{SiO}_3$  has bands at 15.6, 26.5, 29.5, 37.5, and  $49\text{ }\mu\text{m}$  (30) (there is some variation in peak positions among the pyroxenes, but none of the peaks are the same as those of olivine). Thus, all the emission features observed in the 6- to  $45\text{-}\mu\text{m}$  spectrum of Hale-Bopp appear to correspond to those of crystalline olivine rather than pyroxene. A detailed comparison with the spectra obtained for a series of olivines with various Mg/Fe ratios (28) reveals that the peaks of the Hale-Bopp spectrum match those of the Mg-rich olivine (forsterite) more precisely. A Mg-rich composition is consistent with the wavelength of the  $11.3\text{-}\mu\text{m}$  peak and with the dust particle composition measured during the Halley fly-bys (31).

Until now, the nature of cometary dust has been a debated issue primarily on the basis of analysis of the shape of the 9- to  $12\text{-}\mu\text{m}$  emission observed from the ground (2, 5, 29). The only previous spectra at



**Fig. 4.** The 7- to  $45\text{-}\mu\text{m}$  spectrum of Hale-Bopp observed with the SWS on 6 October 1996. The spectral resolution has been degraded to  $\lambda/\delta\lambda \sim 500$ . The ripples in the 12- to  $28\text{-}\mu\text{m}$  region are instrumental (caused by interferences at the surface of the detectors). The instrumental aperture is 14 arc sec  $\times$  20 arc sec up to  $12\text{ }\mu\text{m}$ , 14 arc sec  $\times$  27 arc sec from 12 to  $29\text{ }\mu\text{m}$ , and 20 arc sec  $\times$  33 arc sec above  $29\text{ }\mu\text{m}$ . The subspectra obtained in the different bands of the instrument, which were offset with respect to one another due to different instrumental apertures and to calibration uncertainties, have been scaled to the 6- to  $12\text{-}\mu\text{m}$  band to obtain a continuous spectrum. The dotted line shows a black-body curve fitted to 7.5 and 13 to  $15\text{ }\mu\text{m}$ .

longer wavelengths were from airborne observations of Halley at 1.2 to 1.4 AU, with a resolution of  $\sim 100$  (7) or  $\sim 25$  (6). A peak at  $28.4\text{ }\mu\text{m}$  is present in the first spectrum with possible features at 17, 19.5, and  $23.8\text{ }\mu\text{m}$  (7); these peaks are hardly visible in the other spectra (6). They were tentatively attributed to crystalline silicates. The Hale-Bopp ISO spectrum now suggests that the dust of this comet contains crystalline silicates, and particularly Mg-rich olivine.

Recent ISO observations of the circumstellar disks of Vega-type stars have revealed that the dust shells around these stars also contain crystalline silicates (32, 33). Crystalline silicates were suggested from analysis of the 10- to  $12\text{-}\mu\text{m}$  emission of  $\beta$  Pic (34). Indeed, the spectrum of HD 100546 (an intermediate star between Herbig Ae/Be stars and Vega-like objects) shows features similar to those in Fig. 4 (32). The similarity of these spectra with our spectra of Hale-Bopp establishes a possible link between the primordial solar system dust preserved in comets and the dust around young stars. It has even been suggested that the grains in HD 100546 are being released from cometary bodies colliding with the central star (35).

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11. The field of the 6 October observation was also observed several days later with PHT-S to check that no emission was coming from the background.
12. The SWS observations consisted on 27 September and 6 October of a full 2.4- to  $45\text{-}\mu\text{m}$  spectral scan and a dedicated observation of the 2.6- to  $2.9\text{-}\mu\text{m}$  region. On 6 October, when the comet was at  $r_h = 2.82$  AU and  $\Delta = 3.01$  AU, dedicated observations of regions centered on 3.3, 4.5, and  $6\text{ }\mu\text{m}$  were made in addition.
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17. Production rates in April were  $Q_{\text{H}_2\text{O}} = 2.5 \times 10^{28}$

- $s^{-1}$  from the Hubble Space Telescope [H. A. Weaver *et al.*, *Bull. Am. Astron. Soc.* **28**, 1094 (1996)] and  $1.4 \times 10^{28} s^{-1}$  from the radio (15),  $Q_{CO} = 4.0 \times 10^{28} s^{-1}$  (15). At the end of September,  $Q_{H_2O} = 6 \times 10^{29} s^{-1}$  and  $Q_{CO} = 1.6 \times 10^{29} s^{-1}$  (15). The higher radio  $Q_{H_2O}$  may be due to calibration and model uncertainties, or to comet variability.
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  24. Water exists in two spin species, *ortho* and *para*. Conversion between these two species, either radiatively or through collisions, is forbidden. It is thus believed that its OPR is determined by the temperature at which water was formed and was then preserved [M. J. Mumma, H. A. Weaver, H. P. Larson, *Astron. Astrophys.* **187**, 419 (1987)]. OPRs are thus indicative of the original temperature of cometary material and constrain cometary formation scenarios.
  25. OPRs of  $2.2 \pm 0.1$  and  $3.2 \pm 0.2$  were derived for Halley and Wilson, respectively; it was suggested that this latter value may indicate significant cosmic-ray damage in the outer layers of new comets coming from the Oort cloud [M. J. Mumma, W. E. Blass, H. A. Weaver, H. P. Larson, in *The Formation and Evolution of Planetary Systems*, STScI Workshop (1988)]. It was argued [D. Bockelée-Morvan and J. Crovisier, in *Asteroids, Comets, Meteors III* (Uppsala University, Uppsala, Sweden, 1990), pp. 263–265] that the OPR derived in Halley may have been underestimated by assuming optically thin lines. Because of the lower  $H_2O$  production rate and of the larger geocentric distance of comet Hale-Bopp, the opacity effects are less important in our ISO spectrum; they were estimated to change the intensities of the stronger lines by less than 10%.
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  36. This study was based on observations with ISO, a European Space Agency (ESA) project with instruments funded by ESA Member States (especially the principal investigator countries: France, Germany, the Netherlands, and the United Kingdom) and with participation of ISAS and NASA. The ISOPHOT data presented in this paper were reduced using PIA (Interactive Analysis Package), which is a joint development by the ESA

Astrophysics Division and the ISOPHOT consortium led by the Max Planck Institute für Astronomie, Heidelberg. We thank P. Rocher and the Bureau des longitudes,

Paris, for providing ephemeris of the comet.

4 February 1997; accepted 27 February 1997

## Ground-Based Thermal Infrared Observations of Comet Hale-Bopp (C/1995 O1) During 1996

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Thermal infrared (IR) imaging and spectroscopy of comet Hale-Bopp (C/1995 O1) during June, August, and September 1996 traced the development of the dust coma several months before perihelion. Images revealed nightly variations in the brightness of the inner coma from 1 to 12 June that were correlated with the appearance of a northward-pointing jet. The central IR flux increased by a factor of 8 between 1 June and 30 September, and the September data showed IR jets that corresponded to similar structures that were visible in reflected sunlight at shorter wavelengths. At all epochs, 8- to 13-micrometer spectra of the central coma revealed a strong silicate emission feature, including an 11.2-micrometer feature indicative of crystalline olivine, even when the comet was at a heliocentric distance of 4.1 astronomical units.

Comet Hale-Bopp (C/1995 O1) has provided a rare opportunity for observation of a bright, active comet at large heliocentric distances. The comet's high intrinsic brightness is particularly important to IR studies of thermal emission from cometary dust grains because the thermal background radiation from a warm ground-based telescope limits sensitivity. Most comets can thus be studied in detail only when they are within 1 or 2 astronomical units (AU) of the sun, where their dust grains are relatively warm. Hale-Bopp, however, could be detected easily in the thermal IR when it was still far from the sun and its grains were relatively cool. Also, recent advances in two-dimensional array detectors sensitive to IR radiation at wavelengths between 5 and 30  $\mu\text{m}$  allow study of comets at an angular resolution comparable to that of optical and near-IR observations. Here we present 8- to 13- $\mu\text{m}$  images and spectra of Hale-Bopp that were taken with a modern array camera/spectrograph during the summer and fall of 1996, when the comet was still more than 6 months from perihelion.

We observed Hale-Bopp using the SpectroCam-10 imaging spectrograph (1, 2) on the 5-m Hale telescope at Palomar Observatory (3) during three observing runs: 1 to 12 June 1996 (when the comet was at a heliocentric distance  $r_h = 4.2$  AU and a geocentric distance  $\Delta = 3.3$  AU), 4 to 7 August ( $r_h = 3.5$  AU,  $\Delta = 2.7$  AU), and 28 to 30 September ( $r_h = 2.9$  AU,  $\Delta = 3.0$  AU). The comet was observed at least brief-

ly each night except for 3 June. We imaged Hale-Bopp through 1- $\mu\text{m}$  bandpass filters spaced across the 10- $\mu\text{m}$  atmospheric window in order to measure the comet's overall brightness and morphology (Fig. 1). At wavelength ( $\lambda$ ) = 10.3  $\mu\text{m}$ , the inner coma region within a circle 3 arc sec in diameter centered on the nucleus brightened from 1 to 8 Janskys (Jy) between 1 June and 30 September. This change was greater by a factor of 2 to 4 than the approximately 1 to 1.5 magnitude increase in the total visual magnitude reported during this period, due in part to the increasing temperature of the grains. The general brightening was punctuated by a number of outbursts; during some outbursts, the comet's brightness within the 3-arc-sec circle increased by a factor of 2. Similar short-term brightness increases were observed in comet P/Halley (4). A short-term change in the dust production rate would be expected to cause a larger percentage change in the brightness of the inner few arc seconds than in the brightness of the entire coma (4).

On 2 June, when Hale-Bopp was at a typical inter-outburst brightness, the inner coma was nearly symmetric (Fig. 1A). During the first observed outburst on 4 June, a prominent northward-pointing jet appeared (Fig. 1B). The jet varied noticeably from night to night through the remainder of the June run. By August, the jet had evolved into the broader fan that was familiar from optical images (Fig. 1C). In September (Fig. 1D), we detected as many as five jets that appeared to be the thermal IR counterparts of jets seen in reflected sunlight in the optical and near-IR, including a jet pointing to the west, in the direction of the sun. In the 28 September image, the brightness within synthetic apertures of increasing di-

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