s^{-1} from the Hubble Space Telescope [H. A. Weaver *et al., Bull. Am. Astron. Soc.* **28**, 1094 (1996)] and 1.4×10^{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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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 μm allow study of comets at an angular resolution comparable to that of optical and near-IR observations. Here we present 8- to 13-μm 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 Δ = 3.3 AU), 4 to 7 August (r_h = 3.5 AU, Δ = 2.7 AU), and 28 to 30 September (r_h = 2.9 AU, Δ = 3.0 AU). The comet was observed at least briefly each night except for 3 June. We imaged Hale-Bopp through 1-μm bandpass filters spaced across the 10-μm atmospheric window in order to measure the comet's overall brightness and morphology (Fig. 1). At wavelength (λ) = 10.3 μm, 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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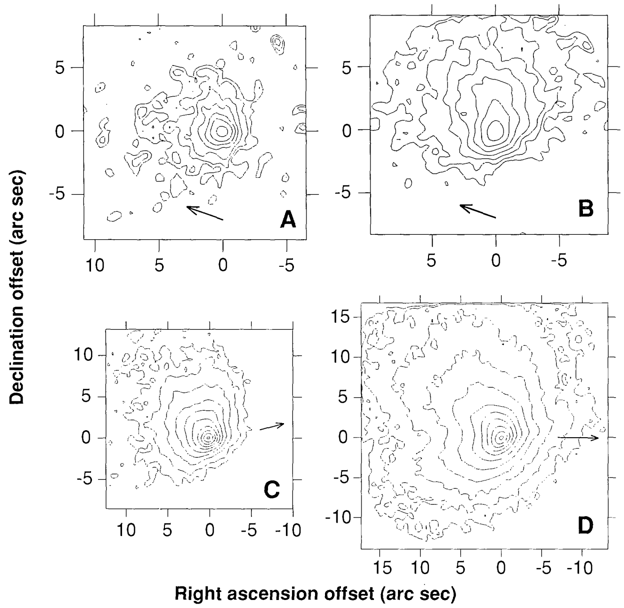

Fig. 1. Four thermal IR images of Hale-Bopp showing the increase in brightness and complexity of the inner coma from June through September 1996. The direction to the sun is indicated by an arrow, and the ratio between adjacent contours is $\sqrt{2}$ in each panel. (**A**) 2.5 June UT (universal time), λ = 10.3 μm, peak contour = 200 mJy arc sec^{-2}. (**B**) 4.5 June UT, 10.3 μm, peak contour = 200 mJy arc sec^{-2}. (**C**) 6.1 August UT, 11.7 μm, peak contour = 800 mJy arc sec^{-2}. (**D**) 28.1 September UT, 11.7 μm, peak contour = 2000 mJy arc sec^{-2}.

ameter d, from 1 to 8 arc sec, centered on the intensity peak, was proportional to d, as expected for a uniform radial outflow of dust. This indicates that short-term temporal variations were not dominating the outflow of dust at this time. There was no sign of an unresolved component at the center that would indicate a direct detection of the nucleus (*5*).

We also obtained 8- to 13-μm spectra of Hale-Bopp's inner coma using SpectroCam-10's low-resolution spectrograph mode. The spectra were taken with a slit 1.0 arc sec wide by 16 arc sec long, positioned at the point of peak brightness at the center of the coma. Here we only discuss the spectra within the 2-arc-sec-long slit segment that was centered on the peak (Fig. 2). On the basis of the behavior of comet Bowell 1982 I (*6*, *7*), we expected that Hale-Bopp might have a coma of large, sublimating icy grains. This raised the possibility of detecting spectral features from ices or organic species in the mid-IR and watching the spectrum change from 4 to 2.5 AU as the grains slowly warmed. However, all the spectra, even at r_h > 4 AU, showed strong silicate emission. The color temperature of the underlying blackbody continuum was significantly greater than the blackbody equilibrium temperatures of 138, 149, and 164 K that were expected at the r_h of Hale-Bopp on the dates of our observations. The shape of the silicate feature is similar to that seen in several comets at smaller r_h, including Halley (0.79 and 1.3 AU), Levy 1990 XX (1.54 AU), and Mueller 1993a (2 AU) (*8*–*11*), although it appeared unusually steep in June and August because of the much lower temperature of the grains. A comparison between the relative emissivity of Hale-Bopp at r_h = 3.53 AU and of comet Levy 1990 XX at r_h = 1.54 AU (*12*) shows a broad maximum near 9.8 μm in both comets that is probably due to glassy or amorphous silicates, and a narrower peak near 11.2 μm due to crystalline olivine (Fig. 3). Thus, at least some of the silicate material in these comets was strongly heated to produce crystalline grains, but whether this heating took place in the interstellar medium or in the solar nebula before comet formation is unknown (*12*). In Hale-Bopp, the 11.2-μm peak was more distinct in June and September than in August (*13*). The silicate feature's flux/continuum ratio increased from 1.9 in June to 2.4 in September. The short-wavelength end of the silicate feature does appear to be significantly broader in Hale-Bopp than in Levy; whether this is an effect of the lower grain temperatures in Hale-Bopp or is due to different intrinsic grain properties may be determined by continued observations as Hale-Bopp approaches perihelion.

The silicate emission and elevated temperature indicate a large population of small (radius less than 1 μm) warm dust grains in the inner coma (*12*). Because these small grains have short dwell time in the inner coma, they must be continuously replaced, either from the nucleus or from sublimation of larger icy particles. The presence of dust jets in the IR images implies that much of this fine material originates from localized active areas on the nucleus.

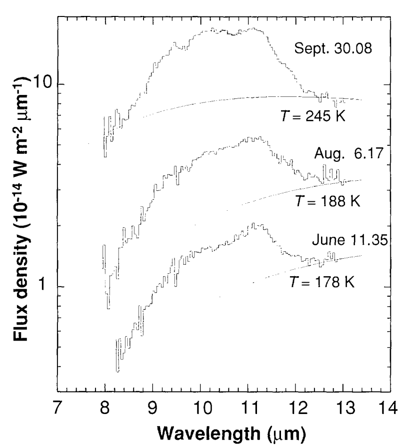

Fig. 2. Thermal IR spectra of Hale-Bopp on 11 June, 6 August, and 30 September 1996, extracted from 2-arc-sec-long segments of the 1-arc-sec-wide slit that were centered on the intensity peak of the coma. A strong silicate emission feature is visible on each date, and blackbody curves drawn through the end points indicate the underlying continuum emission. The blackbody color temperatures from fitting the end points of these spectra are not as reliable as temperatures derived from photometry over a wider wavelength range. The structure visible near 9.5 μm is due to improper cancellation of telluric ozone absorption while dividing by the standard star spectrum.

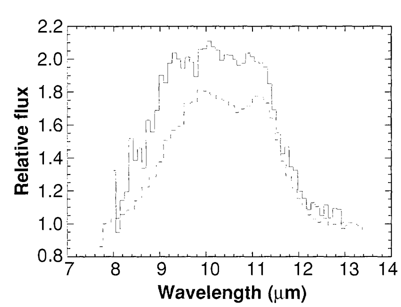

Fig. 3. The 6 August spectrum of Hale-Bopp at r_h = 3.53 AU after dividing by a 188 K blackbody (solid line), showing the relative emissivity across the silicate feature. For comparison, a spectrum of Levy (*11*) taken at r_h = 1.54 AU and divided by a 266 K blackbody is also plotted (dashed line).

REFERENCES AND NOTES

1. The Cornell-built SpectroCam-10 can operate as a camera with a 16 by 16 arc sec field of view and 0.5 arc sec diffraction-limited angular resolution, and as a long-slit spectrograph with resolving power $R = \lambda/\Delta\lambda \approx 100$. Its detector is a 128 by 128 pixel blocked impurity band array manufactured by Rockwell.
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Optical Observations of Comet Hale-Bopp (C/1995 O1) at Large Heliocentric Distances Before Perihelion

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The activity of comet Hale-Bopp (C/1995 O1) was monitored monthly by optical imaging and long-slit spectroscopy of its dust and gas distribution over heliocentric distances of 4.6 to 2.9 astronomical units. The observed band intensities of the NH_2 radical and the H_2O^+ ion cannot be explained by existing models of fluorescence excitation, warranting a reexamination of the corresponding production rates, at least at large heliocentric distances. Comparing the production rate of the CN radical to its proposed parent, HCN, shows no evidence for the need of a major additional source for CN in Hale-Bopp at large heliocentric distances. The dust and CN production rates are consistent with a significant amount of sublimation occurring from icy dust grains surrounding Hale-Bopp.

Most comets brighten sufficiently for detailed observations when their orbit brings them within 3 astronomical units (AU) from the sun. Our knowledge is, therefore, largely based on observations made when the activity is dominated by H_2O sublimation from the nucleus. Few comets have been observed far from the sun, where activity is driven by the second most abundant volatile, CO. Yet, studying the evolution of gas and dust activity over a large range of heliocentric distances, r_h, is important to characterize the composition and structure of the nucleus. The discovery of the bright comet Hale-Bopp (C/1995 O1) at about 7 AU has allowed us to observe the evolution of the comet over a large part of its orbit, as it approaches perihelion (r_h = 0.91 AU) on 1 April 1997.

We monitored Hale-Bopp from April to October 1996 with broadband filters and long-slit spectroscopy at optical wavelengths to determine its activity at r_h from 4.6 AU to 2.9 AU where the changeover from a CO-dominated to a H_2O-dominated activity takes place. We concentrated on observations taken in April, June, August, and October 1996 at the 1.52 m Danish telescope at the European Southern Observatory (ESO), Chile (*1*). In addition, we present a narrow band filter (*2*) image of the CN gas distribution. These observations are complemented by long-slit spectra taken on 10 through 16 September 1996, at the 1.93 m telescope of the Observatoire de Haute Provence (OHP), France (*3*). Enhanced images of jetlike features seen from April to October 1996 (Fig. 1A) showed that some jets appear to bend away from the sun as the cometocentric distance increases. The sense of curvature of the jets suggests that they were bent mainly by solar radiation pressure, and not by radiation of the nucleus. However, long-term morphology changes and changes in intensity of the jets can be used to derive the rotation of Hale-Bopp and the distribution of outgassing areas (*4*). Here, we concentrate on the overall dust distribution and its relation to gas emission in order to understand the evolution of Hale-Bopp's outgassing and unusual as-

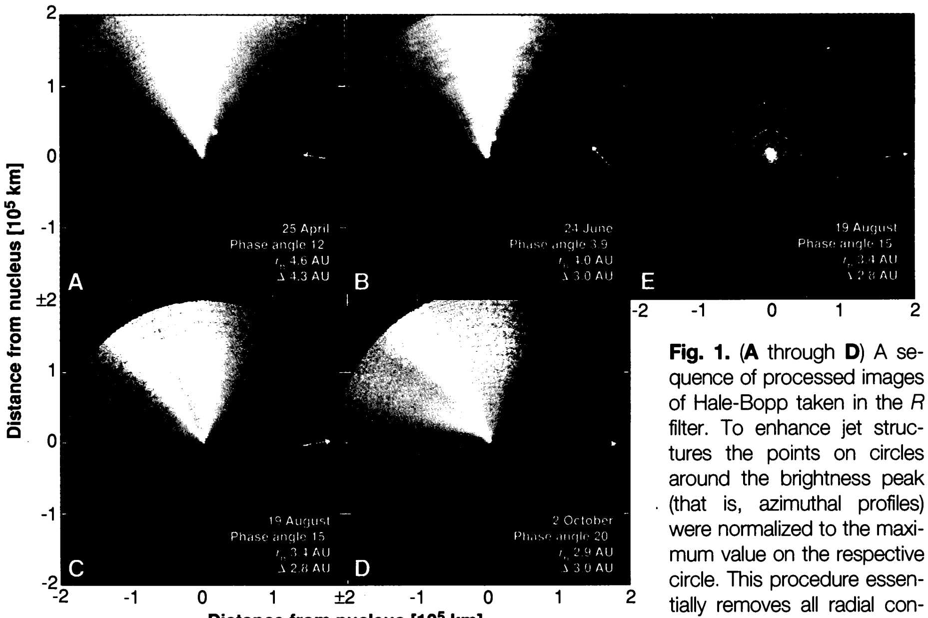

Fig. 1. (**A** through **D**) A sequence of processed images of Hale-Bopp taken in the *R* filter. To enhance jet structures the points on circles around the brightness peak (that is, azimuthal profiles) were normalized to the maximum value on the respective circle. This procedure essentially removes all radial contrast from the images and enhances azimuthal contrast. (**E**) Image of the CN emission at 3880 Å obtained on 20 August 1996. The exposure time is 10 min. An image taken with the blue continuum filter (ESO no. 510) was scaled and subtracted in order to remove the dust contribution. The images are rotated such that celestial North is upwards and East is to the left. The direction of the sun is indicated by an arrow.

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