INFRARED OBSERVATIONS OF DUST EMISSION FROM COMET HALE–BOPP

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Abstract. We present infrared imaging and photometry of the bright, giant comet C/1995 O1 (Hale–Bopp). The comet was observed in an extended infrared and optical observing campaign in 1996–1997. The infrared morphology of the comet was observed to change from the 6 to 8 jet "porcupine" structure in 1996 to the "pinwheel" structure seen in 1997; this has implications for the position of the rotational angular momentum vector. Long term light curves taken at 11.3 μm indicate a dust production rate that varies with heliocentric distance as $\sim r^{-1.4}$. Short term light curves taken at perihelion indicate a rotational periodicity of 11.3 hours and a projected dust outflow speed of $\sim$ 0.4 km s^{-1}. The spectral energy distribution of the dust on October 31, 1996 is well modeled by a mixture of 70% silicaceous and 30% carbonaceous non-porous grains, with a small particle dominated size distribution like that seen for comet P/Halley (McDonnell et al., 1991), an overall dust production rate of 2×10^5 kg s^{-1}, a dust-to-gas ratio of $\sim$5, and an albedo of 39%.

Keywords: Comets: infrared, radio, rotation, surfaces, origin

1. Introduction

Comet Hale–Bopp C/1995 O1 was such an active and bright comet (water gas production rate Q_{OH} @ 1 AU (Hale–Bopp) $\sim 20 \times Q_{\mathrm{OH}}$ @ 1 AU (Halley)) that

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TABLE I

Observation times and observing parameters for C/Hale–Bopp

Obs time (1966 UT)	r (AU)	Δ (AU)	Phase (deg)	Telescope	Instrument	λ (μm)
1996/3–4,9–10	2.8–4.9	3.0–5.1		ISO S/C	ISOPHOT	3.6–160
1996/10/30–11/2	2.54	3.02	17.7	ESO 3.6 m	TIMMI	5–13
1996/12/6–7	2.08	2.88	13.4	ESO 3.6 m	TIMMI	5–13
1997/1/27-29	1.42	2.08	24.4	IRTF 3 m	MIRAC2	2–20
1997/4/1-4	0.915	1.37	47.0	IRTF 3 m	MIRLIN	5–20
1997/4/11–12	0.930	1.47	42.7	IRTF 3 m	MIRAC2	2–20
1997/7/20–27	2.06	2.82	13.8	ESO 3.6 m	TIMMI	5–13
Other data	Hayward and Hanner, Science 275, 1997					5–20

N.B.: Perihelion for the comet occurred at 0.915 AU on 1 April 1997.

it presented a unique opportunity to monitor the infrared emission from the dust coma over many AU and many months, allowing us to study the behavior of a comet as it emitted gas and dust in many different outflow regimes – bare nucleus, CO driven outflow, and water ice dominated emission. In this paper we present preliminary analyses of our long term monitoring program of infrared imaging and photometry of the comet (Table I).

2. Observational Results and Discussion

2.1. 11 μM MORPHOLOGY VS TIME

We were able to observe dramatic changes in the jet structure as the comet approached perigee, some of which may have been due to changing patterns of insolation and projection as the comet moved through its orbit (Figure 1). The morphology of the comet was observed to change from the 6 to 8 jet “hedgehog” structure in 1996 through an intermediate stage presenting a curving sunward fan in early 1997 to the 1–2 jet “pinwheel” structure seen at perihelion/perigee in March–April 1997, and then back to the intermediate stage presenting a curving sun-ward fan in July 1997. The behavior appears symmetric around perigee suggesting that the changes are due to changing observer-comet geometry, and not due to jets turning on and off. The surface brightness of the jets at 11 μm was typically $<$10% of the peak surface brightness of the comet. No rotation against the sky was seen in the “hedgehog” jets, which is quite mysterious, since the morphology of images taken near perigee clearly shows a rotating comet with 1–2 jets emitting spiral arcs of material with an $\sim$11.3 hour periodicity. It is possible that some sort of projection effect or fortuitous insolation and viewing geometry is causing the fixed

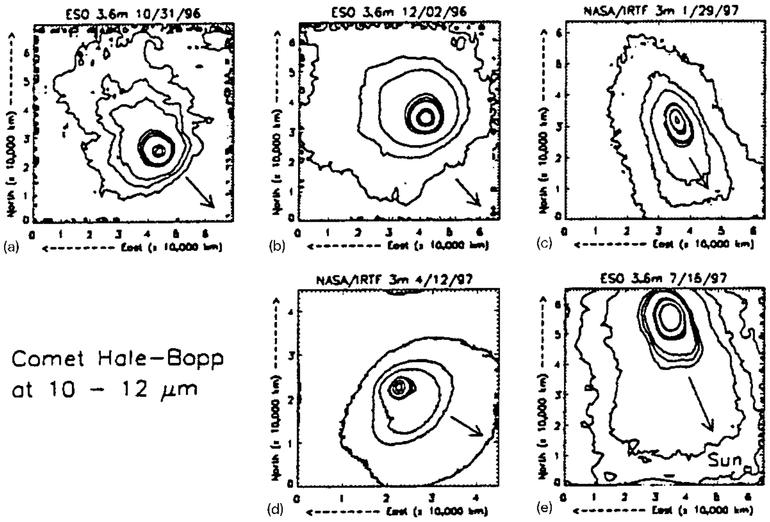

Figure 1. 11 μm comet images. The direction towards the Sun is denoted by the arrow. The data have been baseline and background corrected to ~5% of the back ground and comet signal. The peak fluxes can be found by referring to Figure 2 and Table I. (a) 11 μm ESO C/Hale–Bopp image taken on 1996 October 31, 1996. (b) 11 μm ESO C/Hale–Bopp image taken on December 6, 1996. (c) 11 μm IRTF C/Hale–Bopp image taken on January 29, 1997. (d) 11 μm IRTF C/Hale–Bopp image taken on April 12, 1997. (e) 11 μm ESO C/Hale–Bopp image taken on July 21, 1997.

“hedgehog” structure (e.g., a near polar jet brought into sunlight only near perigee by orbital motion), but it will take detailed modeling to show this.

The 11.3 hour periodicity was found by searching for repetitive morphology (Figure 2); no clear light curve signal was found in the data above the errors for the measurement. Examination of the outflowing arcs created when the rotating jets crossed the terminator and turned off indicates a projected dust outflow speed of $\sim$0.4 km s^{-1}, and structures were found that remain strongly coherent out to $\sim 2 \times 10^4$ km from the nucleus, suggesting a small range in outflow velocities for the dust or a particle size distribution dominated by a small range of dust sizes, consistent with the results of Lien (pers. comm.) and Combi et al. (1997).

2.2. LIGHT CURVES

We have used our imaging photometry to monitor the long term emission of dust by the comet. In Figure 3 we show the 11 μm surface brightness in a $2'' \times 1''$ aperture centered on the comet’s nucleus versus time and heliocentric distance. Data points from ground based measurements by Hayward and Hanner (1997) and ISO spacecraft measurements by Peschke (1997) have been added to extend the baseline in time and heliocentric distance. The best fit to the trend with heliocentric distance has an $r^{-3.9}$ dependence. Since the brightness $I_v \propto Q_{\text{dust}} {*} B_v / v_{\text{dust}}$, while a greybody of constant emissivity in local LTE has an approximately r^{-3} depend-

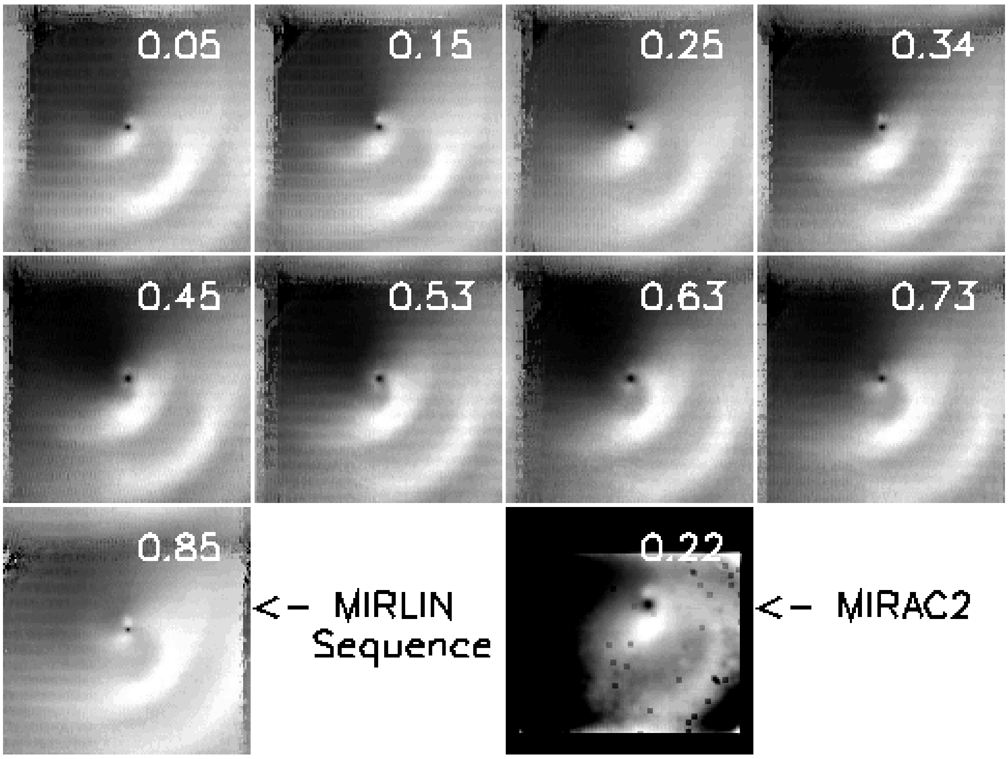

Figure 2. Phase plot of 11 μm images of Comet Hale–Bopp taken near perigee. All images have been divided by a simple $1/\rho$ model to accentutate the spiral jet features. The first 8 images show a time sequence of images of the comet taken April 3–4, 1997 using the MIRLIN camera at the IRTF. Images from ~9.4 hours of the rotation curve were obtained. The relative phase of each image using an 11.3 hour rotation period is printed in the upper right corner of each image. The last image was taken on April 12, 1997 using the MIRAC camera at the IRTF. The similarity between this image and the 0.25 phase image of the MIRLIN dataset demonstrates that the rotational period is 11.3 hours.

ence, and the dust emission velocity goes as $r^{-0.5}$ (Delsemme, 1982), we find that $Q_{\mathrm{dust}} \propto r^{-1.4}$. This variation is in good agreement with the water production rate dependence found by Weaver et al. (1997) using HST measurements: $Q_{\mathrm{H_2O}} \propto r^{-1.1}$ and $Q_{\mathrm{dust}} \propto r^{-1.7}$. Poor agreement is found with their much steeper CO production rate dependence, $Q_{\mathrm{CO}} \propto r^{-4}$, suggesting that the dust emission is driven by water ice sublimation alone.

2.3. SPECTRAL ENERGY DISTRIBUTION

The spectral energy distribution of the comet obtained at ESO on October 31, 1996 is shown in Figure 4. Like the observations of Hayward and Hanner (1997) taken a few months earlier, the spectrum has a pronounced silicate feature approximately

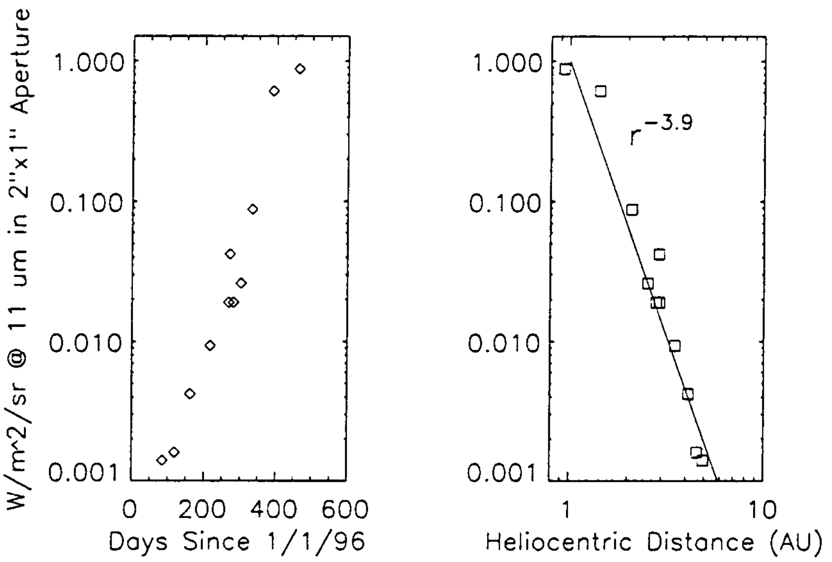

Figure 3. 11 μm cometary light curves. (a) Diamonds – 11 μm light curve for C/Hale–Bopp Mar 1996–Jul 1997, 11 μm flux/beam, plotted vs time. (b) Squares – Same as in (a), but versus heliocentric distance. Solid line – Best-fit power law model to the data, with $r^{-3.9}$ dependence.

four times the underlying continuum and a very large ratio of $T_{\rm color}/T_{\rm local\,bb}$ = 350 K/176 K in the 3–20 μm region. Preliminary results from ISO observations of the thermal emission also show a strong drop off in emissivity at large wavelengths (Peschke, 1997). Applying Mie models including porosity (Lisse et al., 1998) to the multi-wavelength photometry, when the comet was at r = 2.5 AU and Δ = 3.0 AU, we find that the only way to have such warm dust and a large silicate feature is to adopt a McDonnell–Halley particle size distribution dominated by small (1–5 μm) and large ($>$100 μm) particles with solid (i.e., non-porous) grains and a mixed astronomical silicate/amorphous carbon composition in ratio $\sim$70% : 30%. The dust had a very high albedo (defined as the scattered energy/total emitted energy) of $\sim$39% at a phase angle of 17°. Adopting a size-independent dust outflow speed of $0.38 \times r^{-1/2}$ km s^{-1} and using an upper mass cutoff of 1 kg, we find a dust production rate of $\sim 1.4 \times 10^5$ kg s^{-1} and a dust-to-gas ratio of $\sim$5; extrapolation to perihelion using $Q_{\rm dust} \propto r^{-1.4}$ yields a dust production rate at perihelion of 4.6×10^5 kg s^{-1}, in good agreement with the sub-millimeter results of Jewitt and Matthews (1999). Integrating over the whole orbit, assuming $Q_{\rm dust} \sim r^{-1.4}$, we estimate that the comet emitted 1×10^{13} kg of dust; assuming a nuclear radius of 20 km, density of 1 g cm^{-3}, and uniform emission from the entire nuclear surface, we estimate that the comet lost 0.03% of its mass and 2 m of its radius during this apparition.

While the total dust production rate is much greater than typical and the dust to gas ratio is very high, the best fit dust composition and particle size distribution

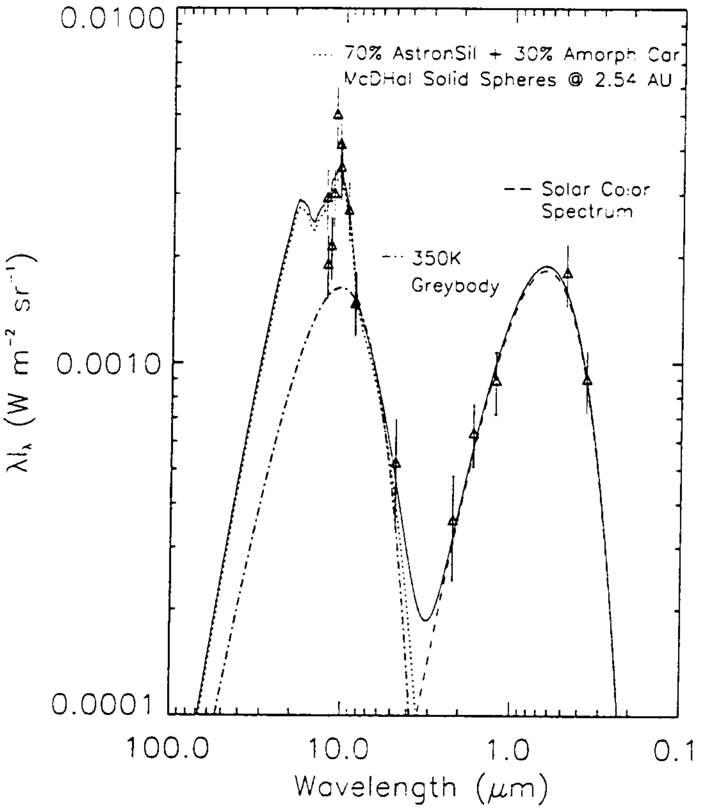

Figure 4. Comet Hale–Bopp spectral energy distribution for a 7″ radius aperture taken on Oct. 31, 1996 at ESO and Lowell. Note the very large and pronounced silicate feature and large superheat versus a 176 K black-body in LTE at 2.54 AU. Dotted curve – best fit modified Mie model: 70% silicates + 30% amorphous carbon solid spheres with a McDonnell Halley (1991) mass distribution. Dashed curve – greybody scattering with solar color spectrum. Solid Curve – best-fit total model. Dash-dotted curve – grey-body fit to the observations, with ~350 K color temperature. Note the poor fit of a simple blackbody to the data.

we find is very typical of dusty comets such as P/Halley 1986, C/Levy 1990K1, and C/Hyakutake 1996B2 (Lisse et al., 1998). This is in good agreement with Schleicher et al. (1997), who have reported that Hale–Bopp is of typical composition when compared to the 85 comets in their optical survey (A'Hearn et al., 1995). The only findings about the dust which are unusual are the predominance of non-porous dust grains and the size-independent particle velocity.

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