

THE INFRARED SPECTRUM OF COMET BRADFIELD (1987s) AND THE SILICATE EMISSION FEATURE

M. S. HANNER¹ AND R. L. NEWBURN¹
 Jet Propulsion Laboratory

R. D. GEHRZ, T. HARRISON, AND E. P. NEY
 Astronomy Department, School of Physics and Astronomy, University of Minnesota

AND

T. L. HAYWARD
 Wyoming Infrared Observatory, Department of Physics and Astronomy, University of Wyoming
 Received 1989 March 13; accepted 1989 July 1

ABSTRACT

Infrared (1–20 μm) observations of comet Bradfield (1987s) from three observatories are reported. Silicate emission is prominent in all the data, from heliocentric distance $r = 0.87$ to 1.45 AU. A CVF spectrum at $r = 1.45$ AU shows a peak at 11.3 μm identified as crystalline olivine; the spectral shape is similar to that in Halley. Dust optical properties are similar to those of the grains in Halley's jets. Dust production rate near perihelion was $\sim 10^6 \text{ g s}^{-1}$ and varied $\propto r^{-2}$. We suggest that some differences in grain properties among comets could result from differences in the thermal history of the nuclear surface and the relative fraction of the dust particles originating in the subsurface icy layer versus the devolatilized mantle.

Subject headings: comets — infrared: spectra — interstellar: grains

I. INTRODUCTION

Comets almost certainly contain interstellar grains in some form. The extent to which the grains have been altered since their existence in the interstellar medium has to be inferred from the properties of the comet grains. For example, the outer few meters of comet nuclei must have been heavily processed by cosmic rays in the Oort cloud. Two key spectral features were discovered in comet Halley—a possible signature of processed organic material near 3.4 μm (Combes *et al.* 1986, 1988; Baas, Geballe, and Walther 1986; Danks *et al.* 1987; Knacke, Brooke, and Joyce 1986; Wickramasinghe and Allen 1986) and a peak in the silicate emission feature at 11.3 μm identified with crystalline olivine (Bregman *et al.* 1987; Campins and Ryan 1989). Both are puzzling because they differ from the corresponding spectral features arising from interstellar grains. Now one wishes to know whether the grains in other comets are similar to those in Halley and whether differences in grain properties among comets can provide clues to their processing history.

Comet Bradfield (1987s) is a long-period comet, but certainly not a dynamically new comet. It was discovered at $r = 1.7$ AU and reached perihelion on 1987 November 7 at $r = 0.87$ AU. The comet exhibited a visual light curve nearly symmetric about perihelion. With a 34° inclination and eccentricity of 0.995, the orbit is fairly stable, and the comet probably had a similar perihelion distance last time (D. K. Yeomans, private communication). In this paper we report our infrared observations of Bradfield from 1987 September to 1988 January, compare the dust optical properties with the dust in Halley, and discuss the nature of the silicate grains.

II. OBSERVATIONS

Infrared observations of the dust coma were obtained at three observatories: the 3 m NASA Infrared Telescope Facility (IRTF), Mauna Kea; the 2.34 m Wyoming Infrared Observatory telescope (WIRO), and the University of Minnesota's O'Brien Observatory 0.76 m telescope (UM). A journal of the observations is given in Table 1, and the observed magnitudes are presented in Table 2. Because of the comet's southern declination and the small angular distance from the Sun, all of the 1987 observations were done at large air mass; thus, extinction is the main source of error.

The UM and WIRO observations used broad-band optical/infrared photometers constructed at the University of Minnesota (Ney 1974; Gehrz, Hackwell, and Jones 1974; Gehrz, Grasdalen, and Hackwell 1987). The same photometer at UM was used for extensive observations of comet Halley (Gehrz and Ney 1986). The UM photometer employs filters centered at 8.5, 10.6, and 12.5 μm , with $\lambda/\Delta\lambda \simeq 10$, while the Minnesota photometer at WIRO contains the set of six intermediate bandpass silicate filters from OCLI, identical to the set in use at the IRTF (Tokunaga *et al.* 1986). Vega (α Lyr) was used to calibrate the October 21 measurements at WIRO, and β Peg was the calibrator for all of the other UM data. The magnitudes of β Peg are shown in Table 3. Beta Peg is apparently variable at the 5%–10% level (Tokunaga *et al.* 1986). The values in Table 3 are consistent with our measurement of β Peg versus α Lyr at the IRTF on 1987 July 19. Mean extinction coefficients were applied in reducing the data.

The WIRO measurements were obtained with a new telephone observing link enabling us to control the computer-operated WIRO telescope remotely from the University of Minnesota (see Gehrz and Hackwell 1978). Data and control functions are transmitted by two 2400 baud telephone lines. A third telephone line provides voice communication with the WIRO technical staff.

¹ Visiting Astronomer, Infrared Telescope Facility, operated by the University of Hawaii under contract from the National Aeronautics and Space Administration.

IR SPECTRUM OF COMET BRADFIELD

313

 TABLE 1
 COMET BRADFIELD (1987s): JOURNAL OF OBSERVATIONS

Date UT	r^a (AU)	Δ^b (AU)	ϵ^c (deg)	Θ^d (deg)	Telescope	Beam Diameter (arcsec)	Throw (arcsec)	Sky Quality	Observations
1987 Sep 21.2	1.21	1.45	55	43	3 m IRTF	6.8	20	Cirrus	8.7–12.5 μm
Oct 21.1	0.92	1.24	48	52	2.3 m WIRO	5	20	Clear	1–18 μm
Oct 22.0	0.92	1.23	48	53	2.3 m WIRO	3	60	Clear	8–12 μm images
Nov 7.0	0.87	1.07	50	60	0.8 m UM	20	30	Cirrus	8.5–12.5 μm
Nov 9.0	0.87	1.05	50	61	0.8 m UM	20	30	Clear	1–18 μm
Nov 13.0	0.88	1.01	52	63	0.8 m UM	20	30	Clear	1.6–18 μm
Nov 18.0	0.89	0.96	54	64	0.8 m UM	20	30	Clear	1–18 μm
Nov 19.0	0.90	0.95	55	64	0.8 m UM	20	30	Clear	1–18 μm
Dec 4.0	1.00	0.85	65	64	0.8 m UM	20	30	Poor	4.8–18 μm
1988 Jan 12.15	1.44	1.08	88	43	3 m IRTF	6.8	20	Clear/day	4.8–20 μm
Jan 13.25	1.45	1.10	88	43	3 m IRTF	7.1	20	Clear	10 μm CVF
Jan 14.15	1.46	1.11	88	42	3 m IRTF	Var. ^e	20	Clear/day	1.2–3.8 μm

^a Heliocentric distance.^b Geocentric distance.^c Sun-Earth-comet angle.^d Sun-comet-Earth angle.^e J, H: 7".6; K: 7".4; L: 6".1; L': 5".8.

Bradfield was observed at the IRTF using the facility InSb (1–3.8 μm) and bolometer (4.8–20 μm) systems. On September 21 the comet was observed at air mass 2.0–2.6 shortly after sunset, while in 1988 January it was observed before sunset near the zenith. Extinction was determined at each wavelength each night by following standard stars over a range in air mass. Magnitudes of the 4.8–20 μm standard stars are given in Table 3. The magnitudes of α Boo and β And at 7.8 and 12.5 μm have been measured relative to α Lyr on one or more nights; the estimated uncertainties are 3%–5%. SJ 9503 was the standard at 1.2–3.8 μm (Elias *et al.* 1982). The aperture diameters listed in Table 1 are the full width at half-maximum obtained by scanning the telescope across a bright star. The field lens in the InSb photometer causes the effective aperture size to decrease with wavelength; the FWHM is 7".6 at J and H, 7".4 at K, 6".1 at L, and 5".8 arcsec at L' (Tokunaga *et al.* 1988).

There will be a small contribution from the comet's outer coma at the position of the reference ("sky") beam. For spherically symmetric radial outflow of dust, the coma brightness in the reference beam will be $I_0(\phi/4\alpha)$, where ϕ = aperture diameter, α = chopping throw, and I_0 = true brightness centered on the comet. The true brightness is therefore approximately 1.06 I_{obs} for the WIRO data, 1.10 I_{obs} for the IRTF data, and 1.20 I_{obs} for the UM data, and, to first order, is independent of wavelength. The magnitudes in Table 2 are given without correction.

Comet observations through the broad, L, L', M, N, and Q filters require a temperature-dependent correction to account for the difference in spectral shape between the radiation from the warm comet dust and the hot standard stars. Corrections of -0.05 and -0.04 mag have been applied to the N and Q magnitudes, respectively (Hanner *et al.* 1984). The corrections for the L and M bandpasses are negligible compared to the observational uncertainties. Because the L bandpass contains both scattered and thermal radiation, the correction is model-dependent. No correction has been applied to our L magnitudes in Table 2. A more detailed discussion of photometric systems is given by Hanner and Tokunaga (1989).

The infrared fluxes are plotted in Figures 1 and 2. The solid curves are dust models discussed in § IV. Excess emission attributed to small silicate grains is present near 10 and 18 μm

in all of the data sets. The color temperature of the underlying continuum between 8 and 12.5 μm is about 15% higher than that of a blackbody in equilibrium with the incident solar flux,

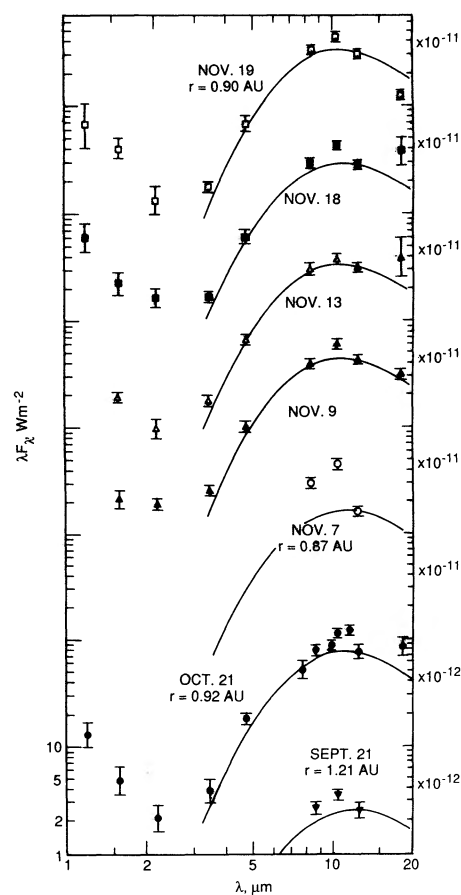


FIG. 1.—Observed spectral energy distribution of comet Bradfield (1987s) in 1987. Data sets are offset by a factor of 10. Solid curves are the predicted continuum emission from dust model 1 (§ IV), normalized to the 12.5 μm flux.

TABLE 2
PHOTOMETRIC OBSERVATIONS OF COMET BRADFIELD (1987s)

Wavelength (μm)	1987 Sep 21.2 ^a IRTF ^b 7 ^c $r = 1.21^d$	1987 Oct 21.06 WIRO 5 $r = 0.87$	1987 Nov 7.0 UM 20 $r = 0.87$	1987 Nov 9.0 UM 20 $r = 0.87$	1987 Nov 13.0 UM 20 $r = 0.88$	1987 Nov 18.0 UM 20 $r = 0.89$	1987 Nov 19.0 UM 20 $r = 0.90$	1987 Dec 4.0 UM 20 $r = 1.00$	1988 Jan 12.15 IRTF ^e 7 $r = 1.44$	1988 Jan 14.15 IRTF ^e $r = 1.46$
<i>J</i> 1.2.....	...	8.72 $\pm$ 0.26	...	6.30 $\pm$ 0.20	...	7.04 $\pm$ 0.33	6.93 $\pm$ 0.50	...	...	10.79 $\pm$ 0.02
<i>H</i> 1.6.....	...	9.00 $\pm$ 0.34	...	7.37 $\pm$ 0.20	7.49 $\pm$ 0.10	7.32 $\pm$ 0.25	6.67 $\pm$ 0.20	...	...	10.34 $\pm$ 0.02
<i>K</i> 2.2.....	...	9.08 $\pm$ 0.31	...	6.71 $\pm$ 0.11	7.42 $\pm$ 0.20	6.86 $\pm$ 0.20	7.11 $\pm$ 0.33	...	...	10.24 $\pm$ 0.02
<i>L</i> 3.5.....	...	6.99 $\pm$ 0.26	...	4.95 $\pm$ 0.10	5.35 $\pm$ 0.11	5.42 $\pm$ 0.10	5.34 $\pm$ 0.11	...	...	9.57 $\pm$ 0.03
<i>L'</i> 3.8.....	...	...	...	...	...	...	...	...	...	9.19 $\pm$ 0.03
<i>M</i> 4.7.....	...	4.36 $\pm$ 0.14	...	2.51 $\pm$ 0.10	2.97 $\pm$ 0.10	3.04 $\pm$ 0.11	2.92 $\pm$ 0.17	3.65 $\pm$ 0.25	6.86 $\pm$ 0.03	...
<i>N</i> 10.1.....	1.26 $\pm$ 0.05	0.30 $\pm$ 0.05	...	...	...	...	...	...	1.66 $\pm$ 0.02	...
8.5.....	...	1.69 $\pm$ 0.21	...	...	...	...	...	...	3.43 $\pm$ 0.05	...
8.7.....	2.07 $\pm$ 0.15	0.90 $\pm$ 0.05	-0.44 $\pm$ 0.10	-0.73 $\pm$ 0.10	-0.47 $\pm$ 0.10	-0.41 $\pm$ 0.10	-0.54 $\pm$ 0.10	-0.82 $\pm$ 0.25	...	...
9.8.....	...	0.40 $\pm$ 0.05	...	...	...	...	...	...	2.42 $\pm$ 0.02	...
10.3.....	1.20 $\pm$ 0.10	-0.03 $\pm$ 0.05	...	...	...	...	...	...	1.63 $\pm$ 0.02	...
10.6.....	...	...	...	...	...	...	...	...	1.48 $\pm$ 0.03	...
11.6.....	...	-0.47 $\pm$ 0.10	-1.66 $\pm$ 0.10	-1.93 $\pm$ 0.10	-1.43 $\pm$ 0.10	-1.55 $\pm$ 0.10	-1.58 $\pm$ 0.10	-1.80 $\pm$ 0.10	...	...
12.5.....	1.0 $\pm$ 0.15	-0.14 $\pm$ 0.10	-1.04 $\pm$ 0.10	-2.07 $\pm$ 0.10	-1.73 $\pm$ 0.10	-1.61 $\pm$ 0.10	-1.70 $\pm$ 0.10	-1.42 $\pm$ 0.10	1.06 $\pm$ 0.03	...
18.1.....	...	...	...	...	...	...	...	...	1.23 $\pm$ 0.07	...
185.....	...	-1.6 $\pm$ 0.15	...	-2.97 $\pm$ 0.15	-3.20 $\pm$ 0.45	-3.19 $\pm$ 0.34	-1.97 $\pm$ 0.15	...	-0.26 $\pm$ 0.06	...
<i>Q</i> 20.0.....	...	...	...	...	...	...	...	...	...	...
									-0.44 $\pm$ 0.03	...

^a UT date.

^b System.

^c Beam diameter in arcseconds.^d r in AU.^e Beam diameter = J, H: 7"6; K: 7"4; L: 6"1; L': 5"8.

TABLE 3
 STANDARD STAR MAGNITUDES

Star	Spectral Type	M 4.8 μm	7.8	8.7	9.8	N 10.1	10.3	11.6	12.5	18.1	Q 20.0	System
5340 α Boo	K2 III	-2.92 ^a	-3.08 ^b	-3.17 ^b	-3.17	-3.17 ^c	-3.17	-3.26	-3.26 ^b	-3.13	-3.13 ^c	IRTF
337 β And	MO III	-1.76 ^a	-1.95 ^b	-1.97	-2.03	-2.04 ^c	-2.04	-2.10	-2.10 ^b	-2.09	-2.09 ^c	IRTF
6406 α Her	M5 II		-3.64 ^b	-3.83	-3.97	-3.94 ^c	-4.02	-4.13	-4.20 ^b			WIRO
8775 β Peg	M2 II	-2.30 ^d		-2.46 ^d		-2.51 ^d			-2.59 ^d	-2.61 ^c		UM

^a Sinton and Tittermore 1984.^b Uncertainty $\geq \pm 0.03$ mag.^c Tokunaga 1984.^d Gehrz *et al.* 1987.

implying that the emission arises mainly from small absorbing grains.

On January 13, a 2% circular variable filter was used with the IRTF Si:As photoconductor to obtain a 16 point spectrum of Bradfield between 7.8 and 12.8 μm . Spectra of the comet were alternated with spectra of β And at air mass 1.0–1.8, and α Tau and α CMa were observed after the comet set. Extinction was determined separately for each of the 16 wavelengths from the three β And spectra. Each individual measurement was reduced to unit air mass before conversion to absolute flux. A high-resolution spectrum of the telluric ozone band at 9.58 μm was used for wavelength calibration.

Bradfield was imaged in the 7–14 μm spectral region on 1987 October 22 UT using a prism array spectrometer with a 3"0 beam and a 60" reference throw. The spectrometer, described by Gehrz, Hackwell, and Smith (1976), was mounted at the Cassegrain focus of the Wyoming infrared telescope. The flux is simultaneously recorded in six channels, centered at 7.92, 8.45, 9.45, 10.69, 11.54, and 12.70 μm . The image was constructed by scanning the chopping secondary in declination at a rate of 7 arcsec s^{-1} , sampling at 1" (chopping frequency is 7 Hz), then stepping the telescope 1" in R.A. and repeating. Four successive images were obtained; the mean air mass was 1.67. Calibration star was α Her, located just 20° from the comet.

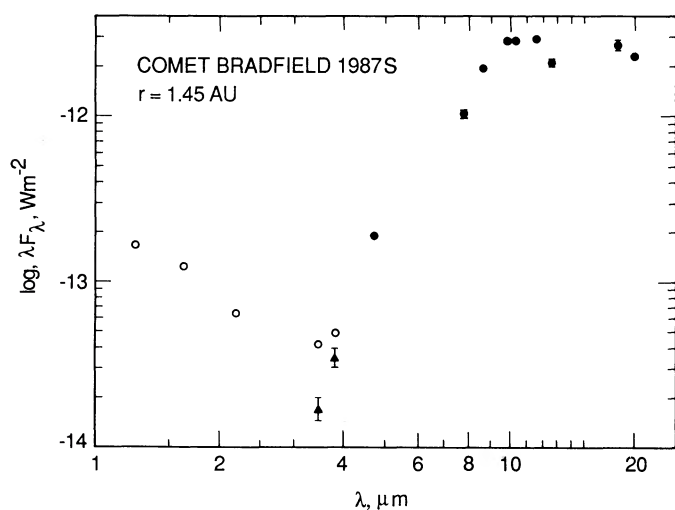


FIG. 2.—Spectral energy distribution of comet Bradfield on Jan 12 (●) and Jan 14 (○) 1988. The InSb data (○) have been scaled to the 6.8 arcsec bolometer beam size assuming flux $\propto \phi$. The triangles are the thermal emission component obtained by subtracting scattered light flux assuming solar spectrum from 2.2 to 3.8 μm .

III. THE SILICATE FEATURE

The CVF spectrum obtained on January 13 is shown in Figure 3. The uncertainty in the absolute flux level is $\sim 10\%$. The filter photometry from the previous night is also plotted in the figure, at the effective wavelengths determined by convolving each filter function with the spectral shape from the CVF spectrum and the sky. The agreement between the filter photometry and the spectrum demonstrates that careful filter photometry can accurately measure the strength of the silicate feature, although of course not its detailed shape. The agreement in the absolute flux levels indicates that the comet did not change its dust output from January 12 to 13.

To compare the shape of the emission feature with other sources, the CVF spectrum was divided by the continuum defined by the dust models in Figure 5. This procedure is physically correct if the silicate grains are at the temperature implied by the continuum. Since the Planck function from 8 to 13 μm is fairly flat in the relevant temperature range, this normalization is unlikely to distort the shape of the silicate feature. Our three Bradfield spectra were individually divided by the continuum normalized to 12.81 μm .

The average of the three normalized spectra and the standard deviations are presented in Figure 4a. Two peaks are apparent, one at 9.7–10.0 μm , similar to the interstellar feature, and one near 11.24 μm . This spectrum is remarkably similar to that of comet Halley at smaller r (Bregman *et al.* 1987; Campins and Ryan 1989), as illustrated in Figure 4b. Bregman *et al.* and Campins and Ryan identify the peak at 11.3 μm with

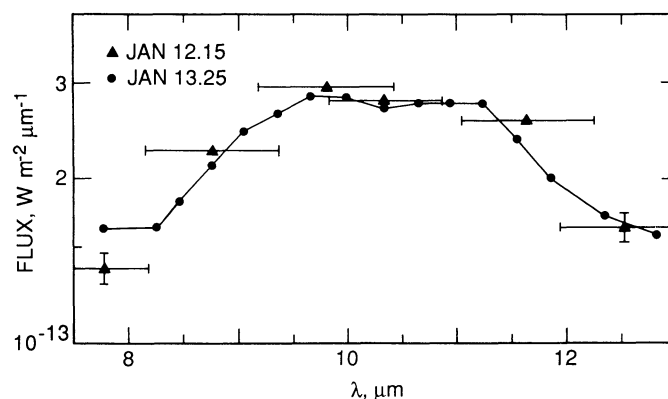


FIG. 3.—CVF spectrum of the dust coma on 1988 Jan 13, (●) compared with filter photometry on January 12 (▲). Horizontal bars are the filter bandpasses convolved with comet spectrum (FWHM).

crystalline olivine. Our spectrum, although the spectral resolution is poorer, indicates the presence of crystalline olivine in Bradfield at 1.45 AU. A higher resolution spectrum of Bradfield at $r = 1.0$ AU, recorded by Russell, Lynch, and Chatelain (1988) clearly shows this peak as well.

Other possible explanations for the peak at $11.3\ \mu\text{m}$, such as SiC or PAHs, can be ruled out from the width of the peak, on abundance arguments, or for lack of corresponding features, such as the $8.6\ \mu\text{m}$ feature present when an $11.3\ \mu\text{m}$ peak is associated with the set of unidentified interstellar infrared bands (Campins and Ryan 1989).

While emission by small crystalline olivine particles matches the $10.5\text{--}12.5\ \mu\text{m}$ portion of the spectrum well (see discussion in Campins and Ryan), other silicates are required to account for the peak near $10\ \mu\text{m}$ and the steep rise from 8 to $9\ \mu\text{m}$. There are three main possibilities.

1. *Mix of crystalline silicate minerals.*—Chondritic interplanetary dust particles (IDPs) examined by Sandford and Walker (1985) fall into three distinct classes based on their $10\ \mu\text{m}$ transmission spectra, corresponding to olivines, pyroxenes,

and hydrated silicates. Bregman *et al.* fitted their Halley spectrum with a mixture of these three IDP spectral types—primarily olivine for the $11.3\ \mu\text{m}$ peak and pyroxenes to fit the $9\text{--}10\ \mu\text{m}$ peak. This approach has the advantage of relating the comet dust directly to the IDPs thought to originate in comets. The disadvantage is that we do not know the history of the IDPs—whether all chondritic IDPs are cometary and whether they could have annealed during their years in the inner solar system or during atmospheric entry.

2. *Partially annealed grains.*—Interstellar silicate grains are thought to be amorphous, because no structure is apparent in the silicate feature. From the laboratory emission spectra recorded by Stephens and Russell (1979), amorphous olivine can explain the broad peak near $10\ \mu\text{m}$ in both the cometary and interstellar spectra while amorphous enstatite particles can account for the steep rise from 8 to $9\ \mu\text{m}$. The comet grains could have a wide range in their degree of structural order, as a result of partial annealing via heating in the solar nebula. Day (1974) showed that the $11.3\ \mu\text{m}$ peak first appeared in the spectrum of an amorphous olivine sample when heated to $\sim 800\ \text{K}$, although long-range structural order did not develop until the grains were heated to $\sim 1000\ \text{K}$. Small crystalline silicate grains have a higher mass absorption coefficient than amorphous grains, by a factor of 3 to 10 (Day 1981). Thus, only a small fraction by mass of crystalline olivine grains could give rise to the observed $11.3\ \mu\text{m}$ peak. Moreover, Aitken *et al.* (1988) have now found evidence for annealed olivine grains in at least one interstellar source.

Partial crystallinity could also explain why no distinct peaks are seen shortward of $22\ \mu\text{m}$ in the $16\text{--}30\ \mu\text{m}$ spectrum of Halley published by Herter, Campins, and Gull (1987), for narrow peaks will show up in the $10\ \mu\text{m}$ stretching mode vibrations for a lesser degree of structural order than required to produce peaks in the $20\ \mu\text{m}$ bending mode vibration (cf. Hanner 1987).

3. *Hydrated silicates.*—Hydrated silicates dominate the composition of type I carbonaceous chondrites; they are the result of low-temperature aqueous alteration. Type II carbonaceous chondrites have about equal proportions of hydrated silicates and olivine; in fact, their spectra look quite similar to the comet Halley and Bradfield spectra, with a small $11.3\ \mu\text{m}$

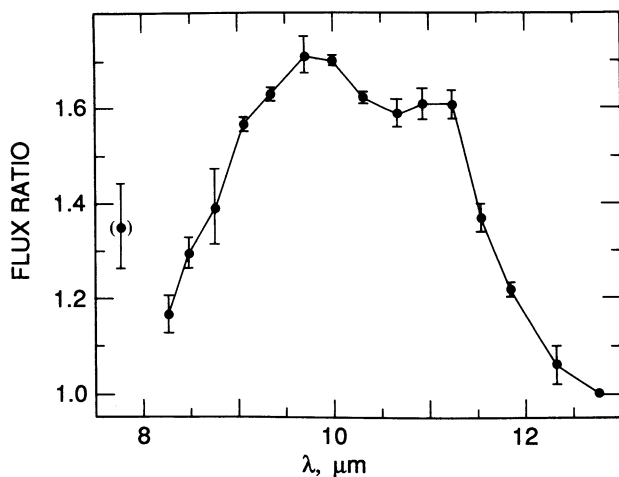


FIG. 4a

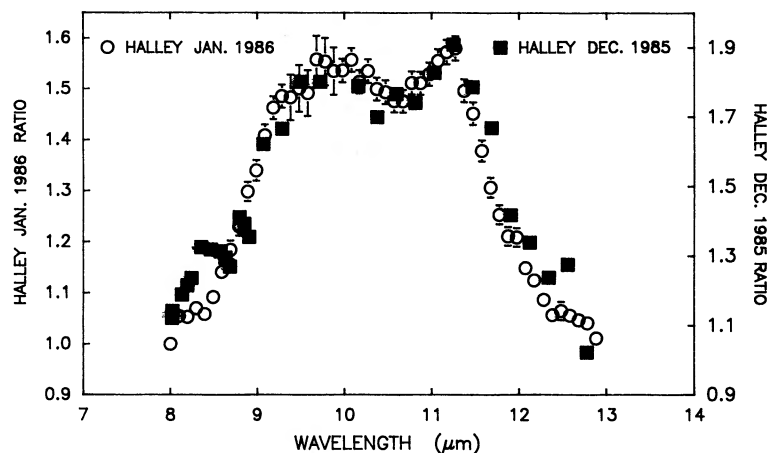


FIG. 4b

FIG. 4.—(a) Spectrum of Bradfield (1987s) divided by the continuum and normalized at $12.81\ \mu\text{m}$. Error bars are the standard deviations from the mean of the three spectra. (b) $8\text{--}13\ \mu\text{m}$ spectra of comet Halley: observed flux divided by continuum. ■ Bregman *et al.* (1987) $r = 1.25$ AU; ○ Campins and Ryan (1989) $r = 0.79$ AU. Figure courtesy of H. Campins.

peak (Zaikowski, Knacke, and Porco 1975). Based on their experiments on the formation of hydrated silicates, Nelson, Nuth, and Donn (1987) suggest that amorphous silicate grains residing on the surface of a comet nucleus could absorb one or more monolayers of water molecules from the outflowing gas and could be converted to hydrated silicates if exposed to temperatures of 300 K or above for a few weeks.

Lawler *et al.* (1988) compared the heterogeneity in the Mg/Fe/Si abundances in the dust grains sampled by the PIA and PUMA experiments on the Halley probes with various classes of meteorites and IDPs. They concluded that only the anhydrous chondritic aggregate IDPs match the Mg-rich silicates and the very wide range in Fe/Si seen in Halley samples; i.e., that there is no positive evidence for the mineralogy of hydrated silicates in the Halley particles. However, PIA and PUMA sampled only the smallest (most numerous) grains with masses $\sim 10^{-16}$ – 10^{-12} g. Whether these grains are representative of the larger grains, which contain most of the mass, is unknown.

Based on present data, then, there is not a unique interpretation of the state of cometary silicates. The three possibilities listed here have, of course, different implications for the evolutionary history of silicate grains since their existence in the interstellar medium. The possibility that the grains are only partially annealed requires the least departure from the interstellar grains. Indeed, with the discovery of annealed grains in astronomical sources, further processing of interstellar silicates may not be required at all. However, annealing of grains after leaving the comet is then required to explain the state of the IDPs.

It would be very helpful to have high-resolution spectra of the silicate feature in comets at $r \sim 0.3$ AU, where the temperature of small grains will be greater than 500 K and one might expect to see further evidence of annealing. It is ironic that the sole spectrum of Kohoutek at $r = 0.31$ AU suffered a data outage from 10.3 to 11 μ m (Merrill 1974). However, the smooth slope in the data from 11.1 to 12 μ m indicates that an olivine peak was not present. Campins and Ryan showed that their Halley spectrum was very similar in shape to the Kohoutek spectrum except for the 11.3 μ m peak. They concluded that thermal processing alone cannot account for the difference between comets; rather, some diversity in the initial cometary material is likely.

IV. DUST PRODUCTION RATE

The rate of dust-mass loss from the nucleus can be estimated from the thermal emission, within the uncertainties discussed below. We have modeled the continuum emission, based on the temperatures for small absorbing grains from Hanner (1983). The temperature is a strong function of size for absorbing grains $\lesssim 2$ μ m in radius; larger grains have a temperature close to that appropriate for a blackbody in equilibrium with the solar radiation. Two slightly different size distribution functions were applied. The first one, described by Hanner (1984) and Hanner *et al.* (1985) has been used to compute dust production rates in several short-period comets. The second model adopts the analytical form proposed by Divine and Newburn (1987) to fit the dust impact data from the *Giotto* Halley probe (McDonnell *et al.* 1987). Both functions have $n(a) \propto a^{-N}$ at large a , with $N = 3.7$ and 3.8, respectively, and both have a free parameter to adjust the peak in the size distribution, in order to match the observed spectral energy distribution. Model 2 has more (hot) submicron grains. The

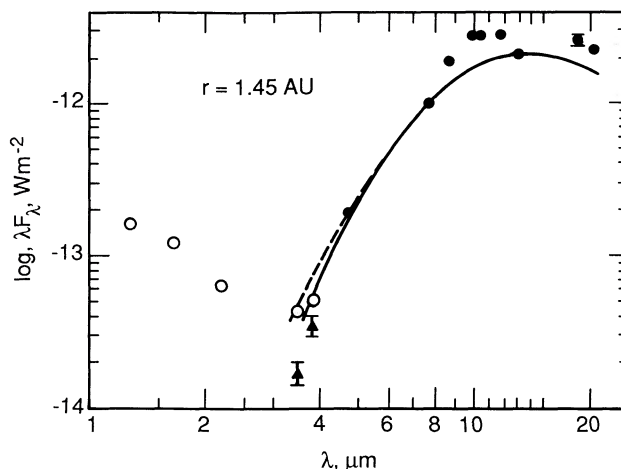


FIG. 5.—Thermal emission on 1988 Jan 12 fitted with models of the continuum emission. Solid line: $n(a) = (1 - a_0/a)^M (a_0/a)^N$, with $a_0 = 0.1$ μ m, $M = 14$, $N = 3.7$ (model 1); dashed line: Divine and Newburn (1987) mass distribution function, $\alpha = 0.94$, $\beta = 0.19$, $\gamma = 1.0$, $m_i = 7.5 \times 10^{-12}$ g (model 2).

parameter values giving the best fit to Bradfield at 1.44 AU also gave the best match to Halley at 0.9 AU (Hanner *et al.* 1987).

Figure 5 shows the predicted thermal emission fit to the January 12 data. At 10 μ m, approximately 75% of the flux is produced by grains with $a > 1$ μ m, while at 4.8 μ m, the grains with $a < 1$ μ m contribute 75% of the flux. The corresponding size distributions in the coma are shown in Figure 6, plotted as cumulative number versus particle mass. For $m \geq 10^{-10}$ g, $N(m) \propto m^{-\alpha}$, where $\alpha = (N - 1)/3$. For our models, $\alpha < 1$, and the mass is concentrated toward the large particles. Thus, the total mass in the field of view depends upon the unknown abundance of large particles, which contribute only a small fraction of the 3–20 μ m thermal emission. The dust impact detector on *Giotto* measured a high concentration of large particles ($m > 10^{-6}$ g), above the extrapolated slope in Figure 6 (McDonnell *et al.* 1987, 1989). The radar echo from Halley also implied the presence of centimeter-size or larger debris (Campbell, Harmon, and Shapiro 1989). Because of their low

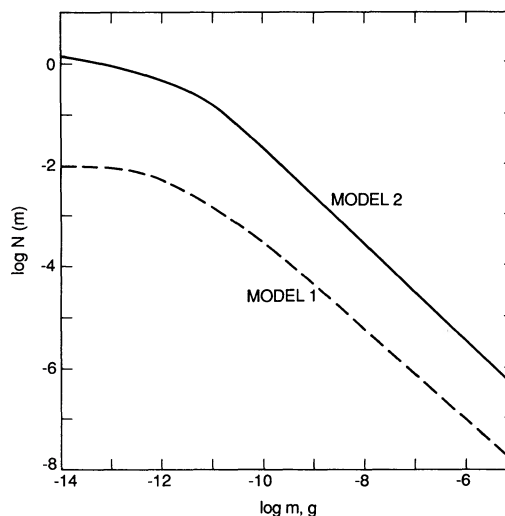


FIG. 6.—Cumulative mass distribution functions fitting the thermal emission on January 12. Solid curve: model 2; dashed curve: model 1.

velocity, however, a high concentration of large dust grains in the coma does not necessarily imply that they dominate the mass flux from the nucleus. One interpretation of the *Giotto* data is that the larger grains were the remnant of an earlier outburst. The predicted continuum based on these dust models, normalized to the $12.5\ \mu\text{m}$ flux, is shown for the other data sets in Figure 1.

To obtain the mass-loss rate, we compute the weighted mean velocity,

$$\bar{v} = \frac{\int a^3 n(a) v(a) da}{\int a^3 n(a) da} \quad (1)$$

following Hanner (1984). For Bradfield at $r = 1.44$ AU, we used the dust velocities, $v(a)$, from Gombosi (1987). These were computed for Tempel 2 at $r = 1.48$ AU from a time-dependent dusty gas dynamical model (Gombosi, Cravens, and Nagy 1985). For other dates, the gas flux per unit surface area was assumed to vary in direct proportion to the total dust production rate, and the velocities were scaled via the relationship shown in Hanner (1984), Figure 4, resulting in a distance dependence, $\bar{v} \propto r^{-1}$. At large particle sizes, $v(a) \propto a^{-0.5}$; thus $\alpha \simeq 1.1$ for the mass distribution leaving the nucleus, and the mass is concentrated toward small grains, near the "knee" in the cumulative mass distribution.

Table 4 presents the computed dust production rates, integrated up to a maximum grain radius of 1 cm. The uncertainty in these numbers is at least a factor of 2, due to the uncertainties in velocities, mean grain density (we assumed $\rho = 1\ \text{g cm}^{-3}$), observed flux, and the abundance of large grains. Models 1 and 2 differed by $\sim 20\%$. If Bradfield has an excess of large particles compared to our assumed $n(a)$, the Q_d computed here could be a lower limit. The method of scaling the velocities accentuates the fluctuations in Q_d . If we had assumed a constant mean velocity for October 21–November 19 ($r = 0.87$ – 0.93 AU); i.e., if higher Q_d implied a larger active surface area, rather than a higher gas and dust flux per unit area, then Q_d on October 21 and November 9 would be $\sim 1.5 \times 10^6\ \text{g s}^{-1}$. A production rate of $\sim 10^6\ \text{g s}^{-1}$ implies an active area of $\sim 10\ \text{km}^2$, assuming a dust/gas mass ratio of 0.5 and a gas flux of $2 \times 10^{-5}\ \text{g cm}^{-2}\ \text{s}^{-1}$. This gives a lower limit of 1.3 km radius for a spherical nucleus if the entire sunward hemisphere were active.

D. G. Schleicher and R. L. Millis (private communication) derived an OH production rate of $\sim 2.5 \times 10^{28}\ \text{s}^{-1}$ on 1988 January 14 and 15. Our dust production rate on January 12–13 was $4 \times 10^5\ \text{g s}^{-1}$. Thus, the dust/water mass ratio was ~ 0.5

TABLE 4
DUST PRODUCTION RATES

Date	$Q_d (\text{g s}^{-1})$
Sep 21.2	5×10^5
Oct 21.0	2×10^6 ^a
Nov 7.0	1×10^6
Nov 9.0	2×10^6 ^a
Nov 13.0	1×10^6
Nov 18.0	1×10^6
Nov 19.0	1×10^6
Dec 4.0	1×10^6
Jan 12.15	4×10^5
Jan 13.2	4×10^5

^a $1.5 \times 10^6\ \text{g s}^{-1}$ if $\bar{v}$ remains constant.

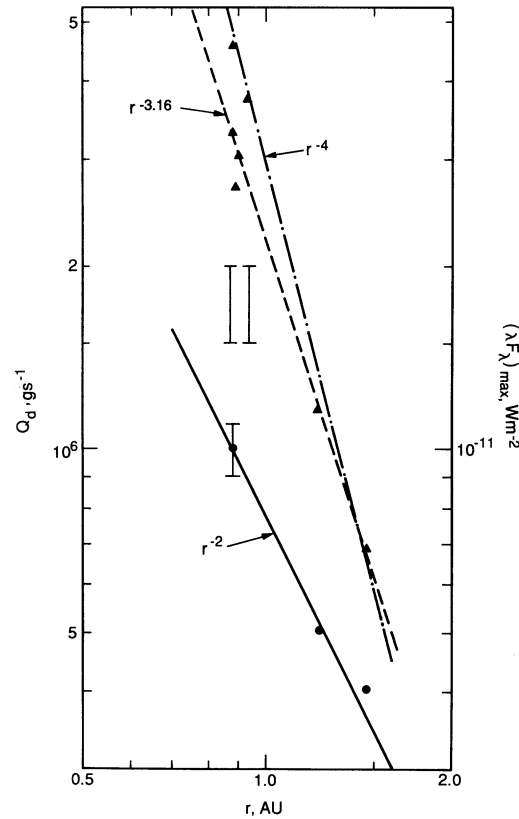


FIG. 7.—Dust production rate, Q_d , (●) and $(\lambda F_\lambda)_{\text{max}}$ (▲) vs. heliocentric distance. The $(\lambda F_\lambda)_{\text{max}}$ have been normalized to 1 AU and to $20''$ beam, assuming isotropic radial outflow. The bar from 1.5 to $2 \times 10^6\ \text{g s}^{-1}$ refers to Q_d on Oct. 21 and Nov 9, while the bar on the point at $10^6\ \text{g s}^{-1}$ displays the range in computed values from Nov 7 to Dec 4.

and the total rate of mass loss for comet Bradfield at $r = 1.45$ AU was $\geq 10^6\ \text{g s}^{-1}$.

In contrast, comet Halley was losing $\sim 2 \times 10^6\ \text{g s}^{-1}$ of small dust grains at 1.5–1.3 AU preperihelion and $\sim 10^7\ \text{g s}^{-1}$ at 0.9 AU pre- and post-perihelion, based on similar dust models (Tokunaga *et al.* 1986; Hanner *et al.* 1987). The fluctuations of a factor 1.5–2 in comet Bradfield's dust production near perihelion indicate nonuniform activity across the nuclear surface, either due to outbursts from pockets of more volatile material or to different active areas rotating into sunlight.

The dust production rates and the quantity $\Delta(\lambda F_\lambda)_{\text{max}}$, which is proportional to the total infrared luminosity (Ney 1982), are plotted versus r in Figure 7. Excluding the two outbursts, Q_d varied approximately as r^{-2} , similar to the new comets Kohoutek (1973 XII) and West (1976 VI) (Ney 1982), but much less steeply than in the case of some short-period comets, such as P/Churyumov-Gerasimenko (Hanner *et al.* 1985). This suggests that the sublimating ice layer is closer to the surface in the new comets and Bradfield and is responding more directly to the incident solar energy than is the case for the more evolved short-period comets.

The infrared luminosity is related to the temperature of the radiating grains and the total number of grains within the field of view by the following equation:

$$L = 4\pi \int a^2 n(a) Q_{\text{abs}} \sigma T^4(a, r) da, \quad (2)$$

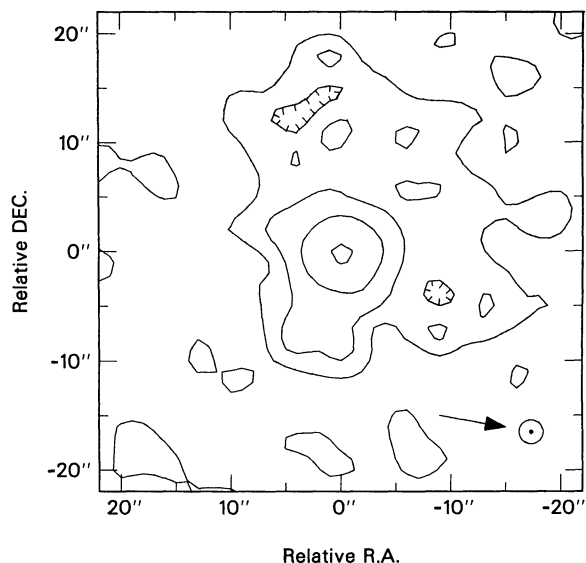


FIG. 8.—Image of the inner dust coma on 1987 October 22. This composite 8.5–11.5 μm image was created by co-adding the fluxes from four spectral channels and four successive images. Beam diameter is $3''.0$ and reference throw is $60''$. The sunward direction is indicated. The contour levels are at 0.2, 0.4, and 0.8 and 1.6 Jy per square arcsec.

where Q_{abs} is the appropriate wavelength-averaged absorption efficiency for a grain of radius a . Since the grain temperature $T(a, r) \propto r^{-1/2}$ (if the grains are not too small), then, $T^4 \propto r^{-2}$ and, for constant outflow velocity, $Q_d \propto r^{-2}$ would give $(\lambda F_\lambda)_{\text{max}} \propto L \propto r^{-4}$. However, in our case, if $\bar{v} \propto r^{-1}$, then the number of grains in the field of view varies as $Q_d/\bar{v} \propto r^{-1}$, and $(\lambda F_\lambda)_{\text{max}} \propto r^{-3}$, close to the $r^{-3.16}$ slope shown in Figure 7.

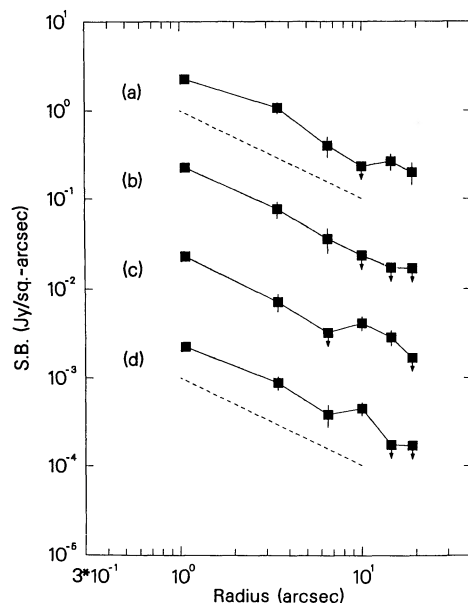


FIG. 9.—Radial brightness gradients as measured from the co-added map. The four curves are at position angles (degrees east of north): (a) 260° , the direction to the Sun; (b) 80° (anti-sunward); (c) 350° ; (d) 170° . The first point of each curve is the mean surface brightness within the 3×3 pixel centered on the nucleus. The remaining points are the mean surface brightnesses within arcs 60° wide, with the outward radii of successive arcs at $5''$, $8''$, $12''$, $17''$, and $21''$ from the nucleus. Dashed line is $1/d$ dependence.

V. 10 MICRON IMAGE

Figure 8 displays a composite image of the inner coma on October 22.0, created by summing channels 2–5 (8.45–11.54 μm), then summing the four images obtained. The beam-switching technique described in Grasdalen *et al.* (1984) was used to subtract the background. There is evidence for a fan-shaped coma in the sunward hemisphere, consistent with the main dust emission occurring from the illuminated side of the nucleus. Dust emission may also be occurring toward the south. The radial gradients in the sunward, anti-sunward, and perpendicular directions are compared in Figure 9. Within the uncertainties the brightness gradient approximates the $1/d$ decrease expected for uniform radial outflow.

A silicate feature was present at all positions within $\sim 12''$ of the center; the signal/noise ratio is not sufficient to detect differences in the shape of the feature. Figure 10 presents the spectrum centered on the brightness peak, at $13''$ south, and integrated over the inner 19 square arcsec.

VI. DUST ALBEDO

Since the total cross section of the dust in the field of view can be derived from the dust model fitting the thermal emission, the average near-infrared albedo of the grains can be computed. We define $A_p(\theta)$ as the ratio of the scattered flux at phase angle θ to that scattered by a white Lambert disk with the same geometric cross section; i.e., $A_p(\theta)$ is the geometric albedo times the normalized phase function (Hanner *et al.* 1981). Assuming that the amount of dust in the field of view did not change from the previous two nights, we find $A_p(\theta) = 0.043$ at J and 0.057 at K on January 14, at phase angle 42° . The albedos at K computed for the other data sets are similar within the $\pm 20\%$ observational uncertainties. The albedos at J

Comet Bradfield 22.0 October 1987

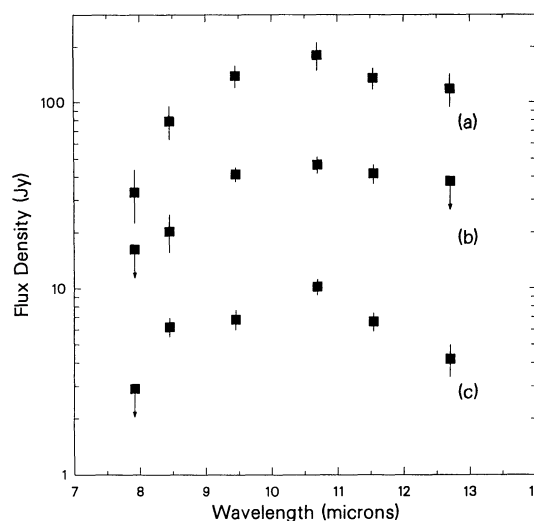


FIG. 10.—Spectra taken with the six-channel spectrometer. The top spectrum (a) was measured from the six images with a $19''$ square centered on the nucleus. Spectra (b) and (c) were measured using standard beam-switched photometry just prior to taking the images. Spectrum (b) was taken with the $3''$ beam centered on the nucleus and (c) was taken $13''$ south of the nucleus.

are considerably higher for the other data sets and, particularly on October 21 and November 9, are beyond what can reasonably be ascribed to measurement or extinction uncertainty.

The albedos at J and K are higher than the albedos derived for other periodic comets via similar dust models, including Halley preperihelion (Tokunaga *et al.* 1986) and P/Churyumov-Gerasimenko (Hanner *et al.* 1985) or even new comet Wilson (1986) at $r = 1.35$ AU (Hanner and Newburn 1989).

Bradfield's colors of $J-H = 0.45$ and $H-K = 0.10$ on January 14 are toward the neutral (less red) end of the range we have measured at the IRTF for comets at $r \leq 2.8$ AU (Hanner and Newburn 1989).

The quantity γ , defined by

$$\frac{(\lambda F_\lambda)_{\max}^{\text{VIS}}}{(\lambda F_\lambda)_{\max}^{\text{IR}}} = \frac{\gamma}{1 - \gamma} \quad (3)$$

is also a useful measure of the average albedo of the grains, since $(\lambda F_\lambda)_{\max}$ is proportional to the total energy under the Planck curve. We find $\gamma = 0.20$ – 0.25 for comet Bradfield, compared with 0.14 – 0.20 for comet Kohoutek at similar phase angles (Ney 1982). If the scattered radiation were isotropic, γ would be a measure of the single scattering albedo. Because the scattering function is strongly peaked in the forward direction, γ represents a lower limit to the single scattering albedo (Ney and Merrill 1976).

VII. DISCUSSION

Do the grains in comet Bradfield differ from those in comet Halley? We have seen that the shape of the silicate feature was similar in the two comets. A similar emission feature at $3.36 \mu\text{m}$, thought to be a signature of organic material, was detected in Bradfield at $r = 0.9$ AU by Brooke *et al.* (1988). Bradfield was unusual in displaying a strong silicate feature at $r = 1.45$ AU, a distance where Halley and other comets have, at most, a broader, weaker feature.

The picture in Halley was complicated by its extreme variability. The strength of the silicate feature varied from day to day (Gehrz and Ney 1986) and with position in the coma (Campins *et al.* 1987; Hanner *et al.* 1987). A higher albedo, and perhaps bluer color as well, were associated with brightness increases (Tokunaga *et al.* 1986; Campins and Tokunaga 1987). The mean $A_p(\theta)$ we derive for Bradfield on January 14 is slightly larger than the maximum Halley values.

Kikuchi *et al.* (1988) measured higher polarization of the scattered light in comet Bradfield than in the quiescent coma of Halley at phase angles $38^\circ < \theta < 65^\circ$. In Halley, higher polarization was observed in the inner coma ("fresh dust") than in the outer coma (Dollfus *et al.* 1988) and increased polarization was associated with outbursts (Kikuchi *et al.* 1987).

In general, then, the optical properties of the dust in Bradfield are similar to the active jets in Halley.

Higher polarization, less red color, higher albedo, and stronger silicate feature could be caused by (1) a higher proportion of small grains, $a \ll \lambda$; (2) a larger relative abundance of silicates; or (3) a difference in the way that the silicate and absorbing material are mixed. For example, it takes only a small fraction of absorbing material by mass to alter the color and albedo of a dielectric such as silicate, if the dark material is physically mixed with the silicate on a fine scale.

The dust detectors on the Halley space probes measured

changes in the size distribution along the probe trajectories, with steeper slope (more small grains) within dust jets (McDonnell *et al.* 1987). The dust composition experiment (PIA, PUMA) recorded differences in the mix of particle compositions along the trajectory, although this instrument sampled only the smallest dust particles (Clark, Mason, and Kissel 1987).

Halley and several low-activity comets detected in the infrared have hot, dark nuclear surfaces, too hot to be compatible with ice sublimation directly from the surface (see review by A'Hearn 1988). The ices sublimate below this mantle and the gas escapes either through cracks and local "bare" areas or directly through the porous mantle. From the *Giotto* images of Halley and the ratio of total gas production to surface area in the comets with known nuclear radii, it appears that most of the gas and dust is emitted from limited active areas.

Where, then, does the dust originate? Are the dust particles from the icy layer below the mantle, entrained by the sublimed gas, or are they dislodged from the surface by the outflowing gas? Surely, the size distribution will differ for these two cases and perhaps the composition as well, particularly if the surface has been altered by cosmic-ray bombardment or solar heating. Silicate grains in such a processed mantle are likely to be physically clumped into larger particles and coated with dark carbonaceous residue of processed organic material. The size distribution of the particles dislodged from the mantle will depend on the friability of the material (see, e.g., Gombosi *et al.* 1985) and may differ for different components.

Therefore, observed differences in dust properties among comets could reflect differences in the properties of the mantle (whether the mantle is primordial, recent thermal history, porosity, friability) and in the relative fraction of the grains coming from the mantle versus the "pristine" interior. One would expect the particles originating in the icy interior to be related more closely to interstellar grains than the dust from the mantle.

Possible interpretations of the similarities and differences between Halley and Bradfield are:

1. The jets in comet Halley and the dust in comet Bradfield contained a higher proportion of particles originating in the subsurface icy layer, including a population of small silicate grains with less carbonaceous material adhering to them than the grains in the mantle. The crystalline olivine grains were present initially in the comet nucleus; the perihelion temperature of Bradfield and Halley is not sufficient to anneal grains exposed on the nucleus surface. In Halley's quiescent periods, or when the jet activity subsided at larger r , grains from the mantle dominated the optical properties.

The more evolved short-period comets which lack a distinct silicate feature may shed their dust mainly from the mantle.

2. The volatility of the organic component in the grains may also have differed. The organic material "gluing" the dust in Bradfield and in the Halley jets may have volatilized readily when exposed to solar heating, causing the grains to fragment, whereas the grains on Halley's nuclear surface contained a more stable, carbonaceous residue, similar to that seen in interplanetary dust particles.

Loss of organic coatings on silicate grains due to heating at smaller r can explain why the silicate feature appears to be stronger in most comets at $r < 1$ AU, but cannot alone explain differences between comets at the same r , without prior thermal processing which makes the mantle material less volatile.

3. There were initial differences in the composition and/or clumping of the grains in the nucleus, perhaps due to formation at different heliocentric distances in the solar nebula.

VII. SUMMARY

In summary, Bradfield was unusual in displaying a prominent silicate feature in our CVF spectrum at 1.45 AU post-perihelion. The shape of the feature was very similar to that observed in Halley at smaller r , with a peak at $11.3\ \mu\text{m}$ identified as crystalline olivine. The silicate feature was strong in all of our data sets near perihelion. The optical properties of the grains were similar to those in comet Halley's dust jets. The peak grain size derived by fitting the infrared spectral energy distribution at $r = 1.44$ AU is the same as that derived for Halley at 0.9 AU. The observed quantity $(\lambda F)_{\lambda_{\text{max}}}$, which measures the total infrared radiation from the dust coma, varied approximately as r^{-3} rather than r^{-4} . On the plausible assumption that the weighted mean dust grain velocity is proportional to the gas flux, $\bar{v} \propto r^{-1}$ and $Q_d \propto r^{-2}$.

We suggest that the differences in grain properties between comets could result from differences in the thermal history of the nuclear surface and in the relative fraction of the dust particles originating in the subsurface icy layer versus the devolatilized surface.

We thank the staff of the WIRO and the IRTF for their support. Don Yeomans kindly provided updated ephemerides. We thank Humberto Campins for discussing his Halley data with us prior to publication and providing Figure 4b. The University of Minnesota infrared astronomy program is supported by NASA, the United States Air Force, the National Science Foundation, and the University of Minnesota Graduate School. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (Planetary Astronomy Program).

REFERENCES

- A'Hearn, M. F. 1988, in *Ann. Rev. Earth and Planetary Sci.*, **16**, 273.
 Aitken, D. K., Roche, P. F., Smith, C. H., James, S. D., and Hough, J. H. 1988, *M.N.R.A.S.*, **230**, 629.
 Baas, F., Geballe, T. R., and Walther, D. M. 1986, *Ap. J. (Letters)*, **311**, L97.
 Bregman, J. D., Campins, H., Witteborn, F. C., Wooden, D. H., Rank, D. M., Allamandola, L. J., Cohen, M., and Tielens, A. G. G. M. 1987, *Astr. Ap.*, **187**, 616.
 Brooke, T. Y., Knacke, R. F., Owen, T. C., Tokunaga, A. T., Mumma, M., Reuter, D., and Storrs, A. 1988, *Bull. AAS*, **20**, 819.
 Campbell, D. B., Harmon, J. K., and Shapiro, I. I. 1989, *Ap. J.*, **338**, 1094.
 Campins, H. C., and Ryan, E. V. 1989, *Ap. J.*, **341**, 1059.
 Campins, H. C., Telesco, C. M., Decher, R., and Ramsey, B. D. 1987, *Astr. Ap.*, **187**, 601.
 Campins, H., and Tokunaga, A. 1987, in *Infrared Observations of Comets Halley and Wilson and Properties of the Grains*, ed. M. S. Hanner (NASA C.P. 3004), p. 1.
 Clark, B. C., Mason, L. W., and Kissel, J. 1987, *Astr. Ap.*, **187**, 779.
 Combes, M., et al. 1986, *Nature*, **321**, 266.
 Combes, M., et al. 1988, *Icarus*, **76**, 404.
 Danks, A. C., Encrenaz, T., Bouchet, P., LeBertre, T., and Chalabaev, A. 1987, *Astr. Ap.*, **184**, 329.
 Day, K. L. 1974, *Ap. J. (Letters)*, **192**, L15.
 ———. 1981, *Ap. J.*, **246**, 110.
 Divine, T. N., and Newburn, R. L. 1987, *Astr. Ap.*, **187**, 867.
 Dollfus, A., Bastien, P., Le Borgne, J.-F., Levasseur-Regourd, A. C., and Mukai, T. 1988, *Astr. Ap.*, **206**, 348.
 Elias, J. H., Frogel, J. A., Matthews, K., and Neugebauer, G. 1982, *A.J.*, **87**, 1029.
 Gehr, R. D., Grasdalen, G. L., and Hackwell, J. A. 1987, in *Encyclopedia of Physical Science and Technology*, **2**, 53.
 Gehr, R. D., and Hackwell, J. A. 1978, *Sky Tel.*, **55**, 466.
 Gehr, R. D., Hackwell, J. A., and Jones, T. W. 1974, *Ap. J.*, **191**, 675.
 Gehr, R. D., Hackwell, J. A., and Smith, J. R. 1976, *Pub. A.S.P.*, **88**, 971.
 Gehr, R. D., and Ney, E. P. 1986, in *Exploration of Halley's Comet* (ESA SP-250), Vol. II, p. 101.
 Gombosi, T. I. 1987, preprint.
 Gombosi, T. I., Cravens, T. E., and Nagy, A. F. 1985, *Ap. J.*, **293**, 328.
 Grasdalen, G. L., Hackwell, J. A., and Gehr, R. D. 1984, *Pub. A.S.P.*, **96**, 1017.
 Hanner, M. S. 1983, in *Cometary Exploration*, ed. T. I. Gombosi, Vol. 2, p. 1.
 ———. 1984, *Adv. Space Res.*, **4**, No. 9, 189.
 ———, ed. 1987, *Infrared Observations of Comets Halley and Wilson and Properties of the Grains* (NASA C.P. 3004).
- Hanner, M. S., Giese, R. H., Weiss, K., and Zerull, R. 1981, *Astr. Ap.*, **104**, 42.
 Hanner, M. S., and Newburn, R. L. 1989, *A.J.*, **97**, 254.
 Hanner, M. S., Tedesco, E., Tokunaga, A. T., Veeder, G. J., Lester, D. F., Witteborn, F. C., Bregman, J. D., Gradie, J., and Lebofsky, L. 1985, *Icarus*, **64**, 11.
 Hanner, M. S., and Tokunaga, A. T. 1989, in *Comets in the Post-Halley Era*, ed. R. L. Newburn, M. M. Neugebauer, and J. Rahe (Dordrecht: Kluwer), in press.
 Hanner, M. S., Tokunaga, A. T., Golisch, W. F., Griep, D. M., and Kaminski, C. D. 1987, *Astr. Ap.*, **187**, 653.
 Hanner, M. S., Tokunaga, A. T., Veeder, G. J., and A'Hearn, M. F. 1984, *A.J.*, **89**, 162.
 Hayward, T., Gehr, R. D., and Grasdalen, G. L. 1986, *Nature*, **326**, 55.
 Herter, T., Campins, H., and Gull, G. E. 1987, *Astr. Ap.*, **187**, 629.
 Kikuchi, S., Mikami, Y., Mukai, T., and Mukai, S. 1988, *Astr. Ap.*, in press.
 Kikuchi, S., Mikami, Y., Mukai, T., Mukai, S., and Hough, J. H. 1987, *Astr. Ap.*, **187**, 689.
 Knacke, R. F., Brooke, T. Y., and Joyce, R. R. 1986, *Ap. J. (Letters)*, **310**, L49.
 Lawler, M. E., Brownlee, D. E., Temple, S., and Wheelock, M. M. 1988, *Icarus*, **80**, 225.
 McDonnell, J. A. M., et al. 1987, *Astr. Ap.*, **187**, 719.
 McDonnell, J. A. M., Green, S. F., Nappo, S., Pankiewicz, G. S., Perry, C. H., and Zarnecki, J. C. 1989, Paper presented at Conference on *Comets in the Post-Halley Era*, Bamberg FRG 1989 April 24-28.
 Merrill, K. 1974, *Icarus*, **23**, 566.
 Nelson, R., Nuth, J. A., and Donn, B. 1987, *Proc. 17th Lunar Planetary Sci. Conf.*, *J. Geophys. Res.* (**92**, No. B4), p. E657.
 Ney, E. P. 1974, *Icarus*, **23**, 551.
 ———. 1982, in *Comets*, ed. L. L. Wilkening (Tucson: University of Arizona Press), p. 323.
 Ney, E. P., and Merrill, K. M. 1976, *Science*, **194**, 1051.
 Russell, R. W., Lynch, D. K., and Chatelain, M. A. 1988, in preparation.
 Sanford, S. A., and Walker, R. M. 1985, *Ap. J.*, **291**, 838.
 Sinton, W. M., and Tittlemore, W. C. 1984, *A.J.*, **89**, 1366.
 Stephens, J. R., and Russell, R. W. 1979, *Ap. J.*, **228**, 780.
 Tokunaga, A. T. 1984, *A.J.*, **89**, 172.
 Tokunaga, A. T., Golisch, W. F., Griep, D. M., Kaminski, C. D., and Hanner, M. S. 1986, *A.J.*, **92**, 1183.
 ———. 1988, *A.J.*, **96**, 1971.
 Wickramasinghe, D. T., and Allen, D. A. 1986, *Nature*, **323**, 44.
 Zaikowski, A., Knacke, R. F., and Porco, C. C. 1975, *Ap. Space. Sci.*, **35**, 97.

R. D. GEHRZ, T. HARRISON, and E. P. NEY: Department of Astronomy, University of Minnesota, 116 Church St., S.E., Minneapolis, MN 55455

M. S. HANNER and R. L. NEWBURN, JR.: Jet Propulsion Laboratory, Mail Stop 169-237, 4800 Oak Grove Drive, Pasadena, CA 91109

T. L. HAYWARD: Box 3905, University of Wyoming, University Station, Laramie, WY 82071