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INFRARED PHOTOMETRY OF THE DUST IN COMETS

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ABSTRACT

Infrared observations of six comets ranging in heliocentric distance from 1 to 5 AU are reported. Data consist of wide and intermediate bandpass filter photometry, 1–20 μm, for periodic comets Stephan-Oterma, Swift-Gehrels, Kearns-Kwee, Gunn, and Grigg-Skjellerup and for parabolic Comet Elias (1981 XV). All of the comets show infrared temperatures hotter than a theoretical black body indicating small absorbing grains. No emission feature at 10 μm was observed within the accuracy of the filter photometry. The photometric system is discussed in detail and temperature-dependent corrections to monochromatic magnitudes are presented.

I. INTRODUCTION

The dust coma in comets is best characterized by infrared measurements. Wide-bandpass photometry, λ 3–20 microns, defines the thermal emission from the grains, while measurements at λ 1–2.5 microns define the scattered light continuum. These data can be used to derive the size distribution and production rate of dust emitted from the nucleus (Hanner 1980, 1983; Campins and Hanner 1982). When an emission feature is observable at 10 microns, the relative abundance of silicate grains can be estimated.

We are conducting a program of infrared photometry of periodic comets with the NASA Infrared Telescope Facility (IRTF) at Mauna Kea in order to study the range in activity and differing dust characteristics exhibited by comets. In this paper we present photometric observations of six comets, spanning a range in heliocentric distance from 1 to 5 AU.

In order to convert the high *precision* of photometric measurements now possible in the infrared at a good site such as Mauna Kea to high *accuracy*, it is imperative that the photometric system be well understood. We discuss here the photometric system we have adopted, in particular the broad bandpass filters at 10 μm (N) and 20 μm (Q) and the set of intermediate bandpass filters used to define the silicate emission near 10 microns. The temperature-dependent corrections to reduce the observed magnitudes to a common reference wavelength are tabulated in the Appendix for the L, M, N, and Q bandpasses. We have done this with the hope that future cometary observations made with the IRTF can be standardized to a common photometric system.

II. OBSERVATIONS

All of the infrared observations were obtained with the 3-m NASA IRTF. The circumstances of the observations are summarized in Table I. A helium-cooled bolometer was used for the observations at 4.8–20 microns and an InSb detector cooled to the temperature of solid nitrogen or liquid helium was used for the observations at 1–4 microns and at 4.8 μm in June 1982.

The photometric observations are presented in Table II. The estimated errors are $\leqslant \pm 0^{m}.1$ at J, H, K, L, and N and $\leqslant \pm 0^{m}.15$ at M, Q, and 8.7–12.5 μm. These errors include uncertainties in extinction, centering on the comet coma, the instrumental magnitude system, and sky noise, but not the uncertainty in the absolute calibration at each bandpass. Temperature-dependent corrections have been applied to the M, N, and Q magnitudes to convert them to monochromatic magnitudes, as described in Sec. IV. These corrections are based on the temperatures in Fig. 1 and Table VI in the Appendix. For Kearns-Kwee, we assumed $T_{\rm eff} = 200$ K. No corrections have been applied to the L magnitudes since this bandpass may include contribution from scattered sunlight as well as thermal emission for comets at large heliocentric distance; hence the corrections will depend on the specific dust model for each comet. No corrections are needed at J, H, and K because the scattered light spectrum is essentially that of the Sun. Although the data on Stephan-Oterma have been published previously (Veeder and Hanner 1981), they are included here to make them consistent with the revised photometric system adopted in this paper.

The extinction coefficients were determined each night from measurements of the standard stars over a range of air mass. The same extinction coefficient was adopted for all filters in the 10-micron window each night. In April and June 1982, the extinction was abnormally high, due to the stratospheric aerosol cloud from El Chicon. For example, k_{λ} $\sim 0^{m}.2$/air mass at 10 microns, June 23–26, about twice the

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TABLE I. Log of observations.

Comet	Date (UT)	R (AU)	Δ (AU)	θ[a] (deg)	Aperture (arcsec)	X[b] (km)	Throw (arcsec)	Filters
P/Stephan-Oterma (1980 X)	Oct. 10.6, 1980	1.73	0.96	151	7.3	5 100	15	*J, H, K, L*
	Nov. 26.5, 1980	1.58	0.62	168	5.6	2 500	20	*M, N*, 8.7, 12.5,
	Mar. 11.4, 1981	1.98	1.39	152	7.3	5 500	20	*J, H, K*
P/Swift-Gehrels (1981 XIX)	Nov. 29.4, 1981	1.36	0.67	136	8.2	4 000	30	*N*, 10.3, 12.5
	Dec. 3.4, 1981	1.36	0.69	136	8.2	4 100	30	*N*, 8.7, 10.3
P/Kearns-Kwee (1981 XX)	Feb. 21.4, 1982	2.32	1.63	159	5.6	6 600	12	*N*
	Feb. 22.4, 1982	2.32	1.63	159	5.6	6 600	12	*J, H, K*
P/Gunn	Feb. 23.6, 1982	2.94	2.30	163	8.2	13 700	30	*J, H, K*
P/Gunn	Apr. 23.5, 1982	2.77	1.79	174	9.6	12 000	30	*J, H, K*
	Apr. 24.5, 1982	2.77	1.79	174	5.6	7 300	30	*J, H, K, L*
	Apr. 28.4, 1982	2.77	1.79	174	5.6	7 300	30	*J, L, M, N, Q*
Elias (1981 XV)	Apr. 23.4, 1982	5.13	4.31	173	9.6	30 000	30	*J, H, K*
	Apr. 24.4, 1982	5.13	4.32	173	5.6	18 000	30	*J, H, K*
	Apr. 28.4, 1982	5.14	4.38	172	5.6	18 000	30	*N, Q*
P/Grigg-Skjellerup (1982a)	Apr. 24.3, 1982	1.03	0.48	107	9.6	3 300	30	*J, H, K*
	Apr. 25.3, 1982	1.03	0.48	106	5.6	1 950	30	*J, H, K, L*
	Apr. 26.3, 1982	1.02	0.47	106	5.6	1 910	30	*J, L*
	Apr. 28.3, 1982	1.02	0.46	104	5.6	1 870	30	*M, N, Q*
P/Grigg-Skjellerup (1982a)	June 23.3, 1982[c]	1.13	0.40	116	5.6	1 620	15	*N, Q*
	June 24.3, 1982[c]	1.14	0.41	118	7.3	2 170	15	*Q*
	June 25.3, 1982[c]	1.14	0.41	118	7.3	2 170	15	*J, K*
	June 26.3, 1982	1.15	0.42	118	7.3	2 230	15	*N*, 8.7–12.5
	June 27.3, 1982	1.15	0.43	119	7.3	2 340	15	*J, K, L, M*
	June 28.3, 1982	1.16	0.43	120	5.6	1 750	15	*M*

[a] Scattering angle (180° − phase angle).
[b] Linear diameter of aperture at comet.
[c] In collaboration with H. Campins.

normal value at Mauna Kea.

The aperture diameters in the Tables correspond to half-power points measured by scanning across a bright star. They relate to the focal plane aperture size in millimeters as follows: 3 mm—5.6″, 4 mm—7.3″, 5 mm—8.2″, 7 mm—9.6″. Although one might expect some difference in the beam profiles between the bolometer and InSb systems, the measured half-power points for the 3–5-mm apertures agreed within 5%; the 7-mm aperture is given here for the InSb. For the three comets measured through more than one aperture at J, H, and K in April 1982, the brightness scales linearly with aperture diameter, as one would expect for isotropic radial outflow. For Grigg-Skjellerup in June 1982, however, the brightness did not increase by 30% at M, N, and Q in going from 5.6″ to 7.3″ aperture. The coma may have been asymmetric or the outer coma may have been too faint to be detected above the sky noise.

Grigg-Skjellerup was moving rapidly near perihelion (Table I). Data taken several days apart in June were converted by Δ^{-1} to $\Delta = 0.42$ AU and the J, H, and K magnitudes were further converted by R^{-2} to $R = 1.14$ AU. The April data are listed separately for each date since the changes from April 25 to April 26 are larger than the estimated errors.

III. STANDARD STARS

The magnitudes we used for the bolometer standard stars are listed in Table III (cf. unpublished Caltech list, with the exception of the 20-μm magnitudes). The magnitudes were self-consistent to within 5% on nights when we observed more than one standard. The 10-μm magnitudes agree to $\pm$ 0^{m}.05 with Gehrz *et al.* (1974) and with the Arizona magnitudes as quoted in Morrison and Lebofsky (1979). Our magnitudes at 4.8 μm are 0^{m}.04–0^{m}.15 fainter than those listed by Gehrz *et al.* The 20-μm magnitudes are taken from Tokunaga (1983) who has measured the bolometer standard stars in Table III and several AV stars relative to α Lyrae. These data show no evidence that α Lyrae is peculiar relative to other AV stars. The 20-μm magnitudes in Table III are consistent with Q (20.0 μm) = 0.0 for α Lyr. They differ by an average of + 0.14 mag from the 20-μm magnitudes published by Morrison and Simon (1973) and by an average of + 0.06 mag from the 19.5-μm magnitudes of Gehrz *et al.*

The magnitudes in the Caltech list deviate from a black body spectrum between 8.7 μm and 12.5 μm by ~15% for the "well-behaved" K stars α Tau and α Boo and by up to 30% for α Her (*M 5II*). A spectral scan of α Boo by Hackwell (1972) can be fit satisfactorily by a black body with $T \sim 3800$ K; however, a 15% deviation would be possible within the error bars. The spectrum of α Her (Merrill and Stein 1976) is consistent with the trend in Table III. We confirmed this trend by observing α Tau versus α CMa through the five filters; we find $m(\alpha$ CMa) − $m(\alpha$ Tau) increases by ~10% from 8.7 μm to 12.5 μm. Many M stars have circumstellar dust emission near 10 microns (e.g., α Ori and μ Cep, Merrill and Stein 1976; α Sco, Hackwell 1972; α Her, Woolf 1973). The standards in Table III, except α Her, showed no evidence of excess emission in the 11 μm/3.5 μm flux ratio measured by Gehrz and Woolf (1971). In fact, we did not use α Her as a standard for the narrowband 8.7 μm–12.5-μm observations.

InSb standard stars at J, H, K, and L have been taken from Elias *et al.* (1982). BS 5447 ($M = 3.45$) was used as a standard for Grigg-Skjellerup at 4.8 μm. More work is needed to tie the fainter standards observable with the InSb at 4.8 μm to the bolometer standards at M.

IV. PHOTOMETRIC SYSTEM

Wide-bandpass photometric data are generally reduced to a reference wavelength defined for each filter ("monochromatic" magnitudes). This reference wavelength is often chosen to be the effective wavelength defined by

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TABLE II. Photometric observations (magnitudes).

Comet	Date (UT)	Aperture (arcsec)	*J* 1.25	*H* 1.68	*K* 2.25	*L* 3.5	*M* 4.8	8.7	9.8	*N* 10.1	10.3	11.6	12.5	*Q* 20.0
Stephan-Oterma	10/10/80	7.3	12.66	12.22	12.03	11.56								
	11/26/80	5.6					7.00	3.22		2.39			1.53	0.31
	03/11/81	7.3	14.40	13.86	13.69									
Swift-Gehrels	11/29/81 } 12/03/81 }	8.2						4.52		3.85	3.87		3.02	
Kearns-Kwee	02/21/82	5.6								7.2				
	02/22/82	5.6	15.54	14.91	14.96									
Gunn	02/23/82	8.2	14.6	14.1	13.85									
Gunn	04/24/82	5.6	13.89	13.43	13.30	13.5								
	04/28/82	5.6								6.26				3.43
	04/23/82	9.6	13.22	12.85	12.67									
Elias	04/24/82	5.6	15.30	14.94	14.97	> 14.55								
	04/28/82	5.6								> 7.0				4.15
	04/23/82	9.6	14.63	14.23	14.19									
Grigg-Skjellerup	04/24/82	9.6	14.04	13.72	13.31									
	04/24/82	5.6	14.54			11.24								
	04/25/82	5.6	14.64	14.22	13.95	11.19								
	04/26/82	5.6	14.91			10.78								
	04/28/82	5.6					7.82			3.44				1.69
Grigg-Skjellerup	06/23/82	5.6								3.94				2.1
	06/28/82	5.6					7.75							
	06/24–27/82	7.3	14.72		13.89	10.27	7.95	4.56	4.28	3.95	3.87	3.43	3.36	2.0

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TABLE III. Adopted magnitudes of bolometer standard stars.

	M			*N*				*Q*
	4.8 μm	8.7 μm	9.8 μm	10.1 μm	10.3 μm	11.6 μm	12.5 μm	20.0 μm
α Boo	− 2.95	− 3.17	− 3.15	− 3.15	− 3.15	− 3.26	− 3.33	− 3.13
α Tau	− 2.77	− 2.98	− 2.99	− 2.99	− 2.99	− 3.08	− 3.14	− 3.09
α Her[a]	− 3.44	− 3.85	− 3.86	− 3.87	− 3.87	− 4.08	− 4.16	− 4.17
μ UMa	− 0.73	− 0.95	− 1.00	− 1.00	− 1.00	− 1.12	− 1.19	− 1.08
β Peg[a]	− 2.21	− 2.45	− 2.53	− 2.55	− 2.55	− 2.64	− 2.70	− 2.61
β And	− 1.80	− 1.97	− 2.05	− 2.07	− 2.07	− 2.14	− 2.18	− 2.09
β Gem	− 0.97			− 1.24				− 1.21

[a] These stars are variable at visual wavelengths and may be variable at 10 μm by approximately 0.05 mag.

$$\lambda_{\text{eff}} = \frac{\int \lambda \phi(\lambda) \xi(\lambda) d\lambda}{\int \phi(\lambda) \xi(\lambda) d\lambda}, \quad (1)$$

where the filter transmission is described by $\phi(\lambda)$ and the sky transmission by $\xi(\lambda)$ (i.e., Low and Rieke 1974). For example, $\lambda_{\text{eff}} = 10.54\,\mu$m for the cooled N filter and Mauna Kea sky.

For a wide bandpass, however, one needs to take into account the spectrum of the observed source. We define the reference wavelength, λ_0, for each of the broad-bandpass filters as the wavelength for which $\overline{B(T)} = B_\lambda(T)$, where $B_\lambda(T)$ is the intensity of the observed source at wavelength λ and

$$\overline{B(T)} = \frac{\int B_\lambda(T) \phi(\lambda) \xi(\lambda) d\lambda}{\int \phi(\lambda) \xi(\lambda) d\lambda}. \quad (2)$$

The detector response and transmission of telescope optics are assumed to be flat across a given bandpass. The numerator of Eq. (1) is the quantity actually measured at the telescope.

The reference wavelength defined in this way will be a function of the temperature of the observed source (or a function of the spectral shape for a nonthermal source). At infrared wavelengths, however, there is no significant difference in the reference wavelength for stellar temperatures, 3800–10 000 K. The reference wavelength for each of the filters *at stellar temperatures* has been calculated using Eq. (2) and cooled filter transmissions. The sky transmission at 3–5 microns and 8–13 microns was measured with a circularly variable filter on a bright standard at the IRTF. The sky transmission across the 20-micron bandpass was taken from Morrison and Simon (1973) for 1.0-mm precipitable H_2O. The reference wavelengths defined in this manner are given in Table IV. These are the reference wavelengths used in the Caltech system (Wilson *et al.* 1972; Beckwith *et al.* 1976).

The measured magnitudes of solar system objects, with temperatures of a few hundred degrees, will need to have a correction applied to convert them to monochromatic magnitudes at the reference wavelength defined for the standard stars. In practice only the wide-bandpass filters require correction. The intermediate-bandpass filters used here are sufficiently narrow that no corrections are needed to an accuracy of 1% for $T \geqslant 200$ K.

Our computed correction factors, $f_{\lambda_0} = B_{\lambda_0}(T)/\overline{B(T)}$ and $\Delta m = m_0 - m'$, are tabulated as a function of temperature in the Appendix, assuming black body spectra. These corrections are on the order of 5% for the *M*, *N*, and *Q* bandpasses. For the *L* bandpass, however, the corrections are large and strongly temperature dependent because the spectrum is very steep near 3.5 μm for temperature $\lesssim 500$ K. The picture is further complicated by the fact that solar system objects at these low temperatures may have a significant contribution from scattered sunlight at 3.5 μm, resulting in a spectrum differing from a black body. Consequently, we have not applied these corrections to the *L* magnitudes in Table II.

At 10 microns, the corrections are not dependent on the night-to-night extinction variations at Mauna Kea. At 20 microns, however, the shape of the bandpass can vary somewhat with the atmospheric water vapor content. Warner (1977) quotes the average day time water vapor at Mauna Kea as 2.0 mm; night-time values are typically lower. Our corrections were computed for 1.0-mm precipitable water. More accurate photometry could be achieved by monitoring the water vapor content each night and applying correction factors for the appropriate sky transmission.

Morrison (1973) discusses monochromatic magnitudes in relation to asteroid observations. He adopts 10.0 μm and 20.0 μm as reference wavelengths for the *N* and *Q* filters, respectively. Low and Rieke (1974) plot corrections to monochromatic magnitudes for their photometric system referenced to 10.6 μm (*N*) and 21 μm (*Q*).

Our adopted fluxes for zero magnitude are compiled in Table IV, from Beckwith *et al.* (1976) and Wilson *et al.* (1972) with the exception of the filters at 9.8, 10.3, and 11.6 microns. For these three filters the fluxes were computed from the flux for zero magnitude at 10.1 microns assuming a 10^4-K black body spectrum. The 20-micron calibration is consistent with Simon *et al.* (1972). The value at 10.1 microns is 3% lower than that used by Morrison (1973) and 8% lower than that of Gehrz *et al.* (1974) when both are converted to 10.1 microns. Further comparison of photometric systems is given by Morrison and Lebofsky (1979). Our fluxes for zero

TABLE IV. Reference wavelengths and absolute flux densities.

	λ_0 (μm)	F_λ for 0.0 mag ($W\,cm^{-2}\,\mu m^{-1}$)
J	1.25	2.9×10^{-13}
H	1.68	1.08×10^{-13}
K	2.25	3.8×10^{-14}
L	3.5	6.9×10^{-15}
M	4.8	2.0×10^{-15}
	8.7	1.96×10^{-16}
	9.8	1.23×10^{-16}
N	10.1	1.09×10^{-16}
	10.3	1.01×10^{-16}
	11.6	6.3×10^{-17}
	12.5	4.7×10^{-17}
Q	20.0	7.3×10^{-18}

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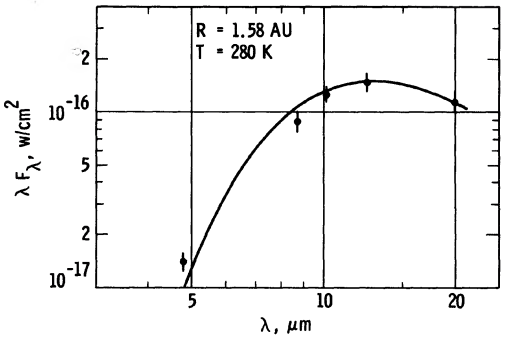


FIG. 1(a). Thermal emission from the dust coma of P/Stephan-Oterma. Curve is best fit to a black body, corresponding to the temperature given.

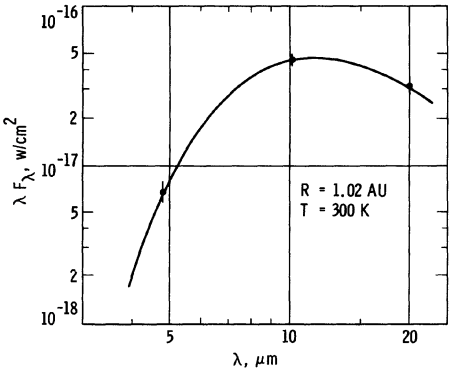


FIG. 1(b). Thermal emission from the dust coma of P/Grigg-Skjellerup, April 28, 1982.

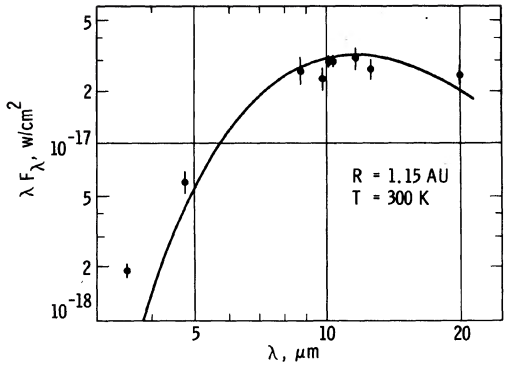


FIG. 1(c). Thermal emission from the dust coma of P/Grigg-Skjellerup, June 23–28, 1982.

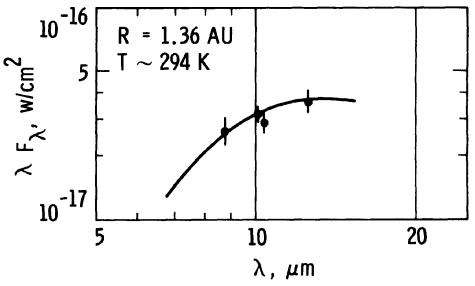


FIG. 1(d). Thermal emission from the dust coma of P/Swift-Gehrels.

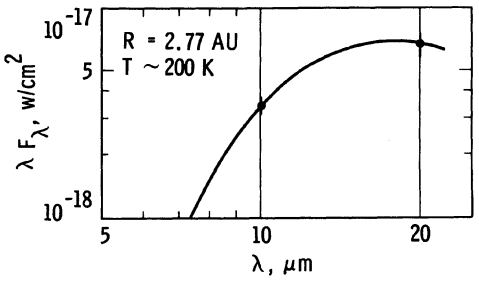


FIG. 1(e). Thermal emission from the dust coma of P/Gunn.

magnitude at 4.8, 10.1, and 20.0 microns are consistent with a 10^4-K black body to 1%; the value at 3.5 μm is consistent with 10.1 μm and a 10^4-K black body to 5%.

During the course of our measurements, we discovered that the 10.3-μm filter had a short-wavelength leak amounting to 10% of the measured stellar flux at 10.3 μm. For cool objects, such as comets, the leak is an insignificant fraction of the 10.3-μm signal. A 1.65% leak was measured at 12.5 μm; the filters at 8.7, 9.8, and 11.6 μm had no short-wavelength leaks contributing $>0.5\%$ of the stellar flux through the filter. The appropriate corrections have been applied to the standard stars in reducing our data at 10.3 μm and 12.5 μm. The leak in the 10.3-μm filter at the IRTF has since been eliminated with a blocking filter.

V. DISCUSSION

The thermal emission data, 3.5–20 μm, are plotted in Figs. 1(a)–1(e). In every case, the effective temperature derived from the thermal spectrum is higher than that expected for a black body in equilibrium at the same heliocentric distance, implying that the grains are $\lesssim 10$ μm size and composed of absorbing material (Hanner 1980). In this respect, these periodic comets are similar to bright nonperiodic comets ob-

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TABLE V. *J*, *H*, and *K* magnitudes reduced to $R = \Delta = 1$ AU and 8-arcsec aperture.

Comet	Date	R (AU)	J	H	K	θ[a] (deg)
Grigg-Skjellerup	04/25/82	1.03	15.00	14.58	14.31	74
	06/27/82	1.15	15.26		14.43	62
Stephan-Oterma	10/10/80	1.73	11.41	10.97	10.78	29
	11/6–8/80[b]	1.61	11.14	10.63	10.45	22
	03/11/81	1.98	12.46	11.92	11.75	28
Kearns-Kwee	02/22/82	2.32	12.79	12.16	12.21	21
Gunn	02/23/82	2.94	11.4	10.9	10.6	17
	04/24/82	2.77	10.66	10.20	10.07	6
Elias	04/24/82	5.13	9.77	9.41	9.44	7

[a] Phase angle (180° − scattering angle).
[b] A'Hearn *et al.* (1981).

served at heliocentric distances $R < 1$ AU. No evidence of a silicate feature near 10 microns is seen in Grigg-Skjellerup or Swift-Gehrels, observed with the narrower filters. However, some silicate grains could be present, their emission masked by that of the absorbing grains, whose thermal spectrum peaks near 10 microns. The 10-μm flux in Stephan-Oterma was measured with the wideband *N* filter, precluding detection of a 10-μm feature; a feature was reported by Campins *et al.* (1982) the following week. Detailed thermal models for the dust grains in these comets will be developed in a separate paper (Hanner, in preparation).

Periodic Comet Stephan-Oterma was extremely dusty, with a bright spherically symmetric coma (Cochran and Barker 1981). Our thermal measurements were taken nine days before perihelion at 1.58 AU. Of the three comets observed at $R < 2$ AU, Stephan-Oterma clearly showed the largest dust production. The *J*, *H*, and *K* colors are similar on October 10, 1980 and March 11, 1981 and are similar to the colors measured by A'Hearn *et al.* (1981) on November 6–8, 1980 and by Campins *et al.* (1982) on December 2, 1980. The roughly constant color implies that neither the mean size nor the composition of the grains changed drastically during this time. The *J*, *H*, and *K* magnitudes are compiled in Table V, reduced to $R = \Delta = 1$ AU and to an aperture of 8-arcsec diameter, assuming the coma brightness is proportional to aperture diameter. The intrinsic brightness increased by 30% from October 10 ($R = 1.73$ AU) to November 7 ($R = 1.61$), then faded by a factor of 3.3 as the comet receded to $R = 2$ AU.

In contrast, Grigg-Skjellerup was a small dust-poor comet. We observed the comet three weeks before its perihelion at 0.99 AU and again six weeks after perihelion. It was the intrinsically faintest of the six comets we observed, as evident from the reduced magnitudes in Table V. The large scatter in the June data [Fig. 1(c)] may have been caused by the volcanic haze layer which was bright and variable during this time or may indicate variable activity in the comet.

Swift-Gehrels was also a dust-poor comet. Most of the visual light arose from gaseous emission lines (Cochran, private communication 1982). We observed Swift-Gehrels a few days after its perihelion on November 27.5 at 1.361 AU. Because of poor weather, only measurements in the 10-micron window were obtained; no silicate emission was observed. *JHK* magnitudes were measured by Campins (private communication 1982) on November 29.

Kearns-Kwee and Gunn represent the class of periodic comets with perihelion beyond 2 AU ($q = 2.22$ AU, $P = 9.0$ yr; $q = 2.46$ AU, $P = 6.8$ yr for Kearns-Kwee and Gunn, respectively). Kearns-Kwee was observed to be extremely dusty; the scattered light continuum accounted for most of the visible light (Cochran, private communication 1982). The temperature excess we observed in Comet Gunn implies grain sizes comparable to those in comets observed at smaller heliocentric distance. Gunn was intrinsically brighter in the near infrared at 2.77 AU than any of the comets we observed at smaller heliocentric distance.

Comet Elias (1981 XV) was observed at $R = 5.13$ AU, the largest heliocentric distance at which a comet has been detected at 20 μm. From Table V one sees that Elias was intrinsically the brightest of the six comets we observed in the near infrared. The 20-μm flux can be compared to Comet Bowell at $R = 4.28$ AU preperihelion (Hanner *et al.* 1981). When reduced to $\Delta = 1$ AU, $Q = 1.64$ for Bowell and $Q = 2.5$ for Elias. Bowell was about a magnitude brighter than Elias in the near infrared at 4.8 AU preperihelion; $J = 8.8$ for $R = \Delta = 1$ AU (Veeder and Hanner 1981).

The $J - H$ and $H - K$ colors are plotted versus scattering angle in Fig. 2. Colors for comets Tuttle, Meier, and Ste-

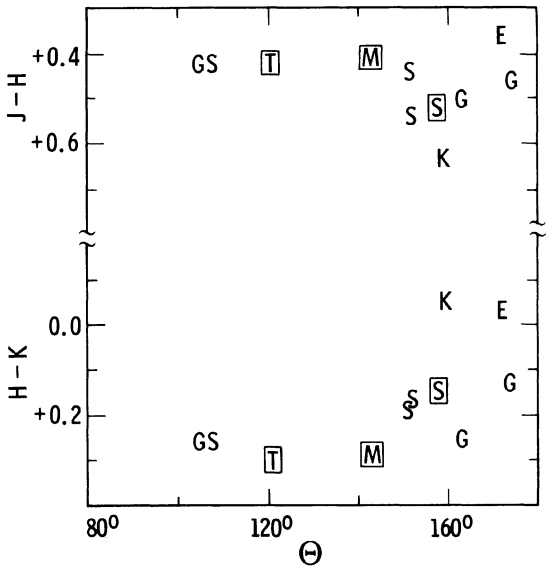


FIG. 2. $J - H$ and $H - K$ colors vs scattering angle θ. Squares are data from A'Hearn *et al.* (1981). Symbols are E: Elias; G: Gunn; GS: Grigg-Skjellerup; K: Kearns-Kwee; M: Meier; S: Stephan-Oterma; T: Tuttle.

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TABLE VI. Conversions to monochromatic magnitudes.

Temperature	*L* 3.5 μm $f_{3.5}$	Δm	*M* 4.8 μm $f_{4.8}$	Δm	*N* 10.1 μm $f_{10.1}$	Δm	*Q* 20.0 μm $f_{20.0}$	Δm
135	0.19	+1.80	0.98	+0.02	0.73	+0.35	1.02	−0.03
150	0.26	1.48	1.01	−0.01	0.80	+0.24	1.03	−0.04
175	0.36	1.11	1.03	−0.03	0.90	+0.12	1.04	−0.04
200	0.46	0.83	1.04	−0.05	0.96	+0.04	1.04	−0.04
250	0.63	0.50	1.05	−0.055	1.03	−0.03	1.04	−0.04
300	0.75	0.31	1.05	−0.055	1.05	−0.055	1.03	−0.04
350	0.83	0.20	1.05	−0.055	1.06	−0.065	1.03	−0.03
400	0.89	0.13	1.05	−0.05	1.06	−0.065	1.03	−0.03
450	0.93	0.08	1.04	−0.05	1.06	−0.06	1.02	−0.02
500	0.96	0.05	1.04	−0.04	1.05	−0.06	1.02	−0.02

phan-Oterma from A'Hearn *et al.* (1981) are also included. The $J - H$ colors seem to be fairly uniform, independent of scattering angle. The $H - K$ colors suggest a possible bluer color near 180° (backscatter). Comet Bowell also had a blue $H - K$ color (+ 0.03) at 176° scattering angle (Veeder and Hanner 1981). Stephan-Oterma showed a color change as well as enhanced intensity in the scattered light at visual wavelengths near 180° (Millis *et al* 1982). Only Comet Elias is bluer than the mean in both $J - H$ and $H - K$. (Perhaps we are seeing icy or ice-coated grains?) Kearns-Kwee is bluer in $H - K$, but redder in $J - H$; this suggests that the H magnitude may be in error by $\gtrsim 0^m1$. Further discussion of J, H, and K colors is given in Veeder and Hanner (1981).

We conclude that the dust properties are not drastically different for dust-rich and dust-poor periodic comets, over a wide range in heliocentric distance. Both Gunn and Elias showed an extensive dust coma at large heliocentric distance; a species more volatile than water ice must be responsible for their activity.

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APPENDIX: CONVERSIONS TO MONOCHROMATIC MAGNITUDES

Table VI summarizes the factors to convert the measured intensity from a thermal source to the intensity at reference wavelength λ_0 for each of the broad photometric bandpasses we used at the NASA IRTF.

The factor $f_{\lambda_0} \equiv B(\lambda_0, T)/\overline{B(T)}$, where $B(\lambda_0, T)$ is the intensity per unit wavelength at wavelength λ_0 and temperature T, and $\overline{B(T)}$ is the averaged irradiance across the bandpass defined by

$$\overline{B(T)} = \frac{\int B_\lambda(T)\phi(\lambda)\xi(\lambda)d\lambda}{\int \phi(\lambda)\xi(\lambda)d\lambda}.$$

The sky transmission $\xi(\lambda)$ was measured at the IRTF across the L, M, and N bandpasses. A computed sky transmission for 1.0-mm precipitable water from Morrison and Simon (1973) was used for the Q filter, 16–26 μm. The filter transmission $\phi(\lambda)$ corresponding to the cooled temperature of operation (~77 K) was used. A black body spectrum was assumed for $B_\lambda(T)$.

The corresponding magnitude corrections are $\Delta m = m_0 - m'$, where m_0 is the monochromatic magnitude at wavelength λ_0, and m' is the observed magnitude. The reference wavelengths satisfy the condition $f_{\lambda_0} = 1.0$ for $T = 4000$–$10\,000$ K.

REFERENCES

A'Hearn, M. F., Dwek, E., and Tokunaga, A. T. (1981). Astrophys. J. Lett. **248**, L147.

Beckwith, S., Evans, N. J., Becklin, E. E., and Neugebauer, G. (1976). Astrophys. J. **208**, 390.

Campins, H., and Hanner, M. S. (1982). In *Comets*, edited by L. L. Wilkening (University of Arizona Press, Tucson), p. 341.

Campins, H., Rieke, G. H., and Lebofsky, M. J. (1982). Icarus **51**, 461.

Cochran, A. L., and Barker, E. S. (1981). Presented at IAU Colloquium No. 61, Tucson, March 1981.

Elias, J. H., Frogel, J. A., Matthews, K., and Neugebauer, G. (1982). Astron. J. **87**, 1029.

Gehrz, R. D., Hackwell, J. A., and Jones, T. W. (1974). Astrophys. J. **191**, 675.

Gehrz, R. D., and Woolf, N. J. (1971). Astrophys. J. **165**, 285.

Hackwell, J. A. (1972). Astron. Astrophys. **21**, 239.

Hanner, M. S. (1980). In *IAU Symposium No. 90*, edited by I. Halliday and B. McIntosh, p. 223.

Hanner, M. S. (1983). *Proceedings of the International Conference on Come-*

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1984AJ.....89..162H

tary Exploration, edited by T. I. Gombosi (Hungarian Academy of Sciences, Budapest), Vol. 2, p. 1.
Hanner, M. S., Veeder, G. J., and Matson, D. L. (1981). Bull. Am. Astron. Soc. **13**, 705.
Low, F. J., and Rieke, G. H. (1974). In *Methods of Experimental Physics* **12**, edited by N. Carelton (Academic, New York), p. 415.
Merrill, K. M., and Stein, W. A. (1976). Publ. Astron. Soc. Pac. **88**, 285.
Millis, R. L., A'Hearn, M. F., and Thompson, D. T. (1982). Astron. J. **87**, 1310.
Morrison, D. (1973). Icarus **19**, 1.
Morrison, D., and Lebofsky, L. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona Press, Tucson), p. 184.
Morrison, D., and Simon, T. (1973). Astrophys. J. **186**, 193.
Simon, T., Morrison, D., and Cruikshank, D. P. (1972). Astrophys. J. Lett. **177**, L17.
Tokunaga, A. T. (1983). Astron. J. **89**, 172.
Veeder, G. J., and Hanner, M. S. (1981). Icarus **47**, 381.
Warner, J. W. (1977). Publ. Astron. Soc. Pac. **89**, 724.
Wilson, W. J., Schwartz, P. R., Neugebauer, G., Harvey, P. M., and Becklin, E. E. (1972). Astrophys. J. **177**, 523.
Woolf, N. J. (1973). Publ. Astron. Soc. Pac. **85**, 730.

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