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THE SPECTRAL APPEARANCE OF COMETS FROM 5-20μm: A SURVEY OF THE DATA

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1. THE "EXPECTED" SPECTRAL APPEARANCE OF COMETS

Based on the concept of comets as being conglomerates of rocks and ices, we expect them to reflect these components in their emission spectra. Silicate materials (rocks) are common in many astronomical environments and show prominent features at about 10 and 18μm. Carbon, either in its amorphous or graphitic form, should be abundant, but is much more difficult to detect spectroscopically since it has no strong features (except for the hydrogenated forms). Ices are surely present in comets, but they are difficult to detect since they are volatile enough to dissipate when the comet is bright enough to be easily observed in the IR, with present equipment. There are certainly other materials present in comets, but the ones listed above should be the most common and thus dominate the thermal IR spectrum.

2. THE OBSERVATIONS

Table 1 summarizes most of the IR observations made on comets between 5 and 20μm. They fall into three broad categories: (1) filter photometry with spectral resolution R $\approx$10, (2) CVF (circular variable filter wheel) spectroscopy with R$\approx$50, and (3) spectra obtained with multi-detector grating spectrometers and R$\approx$50-100.

2.1 Filter Photometry

Photometry with narrowband (R$\approx$10) or broadband (R$\approx$ 2) filters has shown several important characteristics of cometary dust that are listed below.

1. Thermal emission is from dust at a temperature above that expected from a blackbody at the same distance from the sun (in some comets), indicating that the dust particles are small (Becklin and Westphal, 1966; Maas, Ney, and Woolf, 1970).

2. Silicates are a prominent component of comet dust since the spectra show a strong emission feature at 10μm (Maas, Ney, and Woolf, 1970).

3. Large particles, which are present along with small particles in cometary comae, do not show the 10μm silicate feature, and are not hotter than a blackbody. This effect was striking in comet Kohoutek which had hot dust with a silicate feature in the tail and coma, while the anti-tail dust was much cooler and did not show a silicate feature (Ney, 1974).

4. The apparent strength of the silicate feature varies with distance from the sun; and beyond about 1.5 A.U. there are no observations of a silicate feature in any comet (Rieke and Lee, 1974; Hanner *et al.*, 1987). This may in some part be due to the paucity of observations of comets at distances beyond 1 A.U. from the sun.

5. The data indicate that a single blackbody temperature does not completely describe the dust emission, but that a mixture of particle sizes (and thus emission from a range of temperatures) is needed to fit the spectra.

2.2 CVF Observations

Filter photometry has provided insight into the bulk nature of cometary dust and has even shown the broad emission features that identify silicates as a component material. To provide more detailed compositional information, higher resolution spectra are needed. The earliest of these spectra were obtained with single-detector systems using a continuously variable circular filter (CVF) and covered the wavelength range from 8-13μm. A spectrum of comet Bennet (Hackwell, 1971) had poor signal to noise, but still showed a strong silicate emission band at 10μm. Merrill (1974) obtained an excellent spectrum of comet Kohoutek, but had missing data in the 11μm region. It showed a smooth silicate emission, similar to that seen in stars.

2.3 Multi-Detector Grating Spectrometers

Since CVFs obtain data one point at a time, spectra can only be obtained of bright comets. Multi-detector spectrometers can cover the entire 8-13μm range simultaneously, thus providing the opportunity to obtain good quality spectra of considerably fainter comets. Hanner *et al.* (1984, 1985a, 1985b) observed three comets between 8-13μm which showed smooth spectra consistent with at most a 20 percent contribution from small silicate grains (comets Grigg-Skjellerup, Churyumov-Gerasimenko, and IRAS-Araki-Alcock). Feierberg *et al.* (1984) obtained similar results for comet IRAS-Araki-Alcock. Comet Halley was quite different, showing a strong silicate emission spanning the entire 8-13μm region, and it was the first comet to show structure in the 10μm silicate band indicative of a specific mineral type, olivine (Bregman *et al.*, 1987). The data also compared well with a spectrum generated from a combination of laboratory spectra of interplanetary dust particles as long as the mix was dominated by olivine-type material. Comet Giacobini-Zinner (Bregman, unpublished) shows similar structure, but the features are much weaker.

Details of the 20μm region are much less certain. Photometry shows excess emission consistent with silicate emission (when there is a 10μm silicate emission feature), but the single spectroscopic observation of a comet in this region (of Halley by Herter *et al.*, 1986) does not show the silicate feature at the expected strength.

TABLE 1
IR SPECTRAL OBSERVATIONS OF COMETARY DUST 5-20μm
(Through the 20th ESLAB Symposium on the Exploration of Halley's Comet)

COMET	TYPE OF OBSERVATION	REFERENCE
Ikeya-Seki	photometry	Becklin, E.E., and Westphal, J.A. 1966, Ap.J., **145**, 445.
Bennet	photometry 2-20μm	Maas, R.W., Ney, E.P., and Woolf, N.J. 1970, Ap.J.Lett., **160**, L101.
	CVF 8-13μm	Hackwell, J.A. 1971, Observatory, **91**, 33.
	photometry .5-18μm vs. R. Comets Enke, Bradfield, and Kohoutek too.	Ney, E.P. 1974b, ICARUS, **23**, 551.
Kohoutek	photometry .5-18μm nucleus, anti-tail	Ney, E.P. 1974a, Ap.J.Lett., **189**, L141.
	photometry 2.2-22.5μm vs. R	Rieke, G.H. and Lee, T.A. 1974, Nature, **248**, 737.
	photometry 1-20μm vs. R, polarimetry 1.03, 1.65μm	Noguchi, K., Sato, S., Maihara, T., Okuda, H., and Uyama, K. 1974, ICARUS, **23**, 545.
	photometry .5-18μm vs. R. Comets Enke, Bradfield, and Bennet too.	Ney, E.P. 1974b, ICARUS, **23**, 551.
	photometry 1.25-12.5 μm vs. R and aperture	Gatley, I., Becklin, E.E., Neugebauer, G., and Werner, M.W. 1974, ICARUS, **23**, 561.
	CVF 8-13μm	Merrill, K.M. 1974, ICARUS, **23**, 566.
	photometry 8.8-21μm vs. R.	Zeilik, M. and Wright, E.L. 1974, ICARUS, **23**, 577.
West	photometry .5-18μm vs. R.	Ney, E.P. and Merrill, K.M. 1976, Science, **194**, 1051.
		Kawara, K., Kobayashi, Y., Maihara, T., Noguchi, K. Okuda, H., Sato, S., Iijima, T., and Ono 1978, PASJ, **30**, 149.
Kobayashi-Berger-Milon	photometry .7-12.5μm also West and Bradfield	Ney, E.P. 1982, in Comets, ed. Wilkening, (The University of Arizona Press: Tuscon), 323.

Bradfield	photometry .7-12.5µm also West and K-B-M	Ney, E.P. 1982, in Comets, ed. Wilkening, (The University of Arizona Press: Tuscon), 323.
	photometry .5-18µm vs. R. Comets Enke, Kohoutek, and Bennet too.	Ney, E.P. 1974b, ICARUS, **23**, 551.
Stephen-Oterma	photometry 4.8-20µm	Hanner, M., Tokunaga, A.T., Veeder, G.J., and A'Hearn, M.F. 1984, A.J., **89**, 162.
Swift-Gehrels	photometry 4.8-12µm	
Gunn	photometry 10&20µm	
Grigg-Skjellerup	photometry 3.5-20µm	
Grigg-Skjellerup	multichannel spectrometer, 8-13µm	Hanner, M., Aitken, D., Roche, P. and Whitmore, B. 1984, A.J., **89**, 170.
IRAS-Araki-Alcock	multichannel spectrometer, 8-13µm	Feierberg, M.A., Witteborn, F.C., Johnson, J.R. and Campins, H. 1984, ICARUS, **60**, 449.
	multichannel spectrometer, 8-13µm CVF 2.2-4.0µm	Hanner, M.S., Aitken, D.K., Knacke, R., McCorkle, S., Roche, P.F. and Tokunaga, A.T. 1985, ICARUS, **62**, 97.
	IRAS photometry	Walker, R.G., Aumann, H.H., Davies, J., Green, S., DeJong, T., Houck, J.R. and Soifer, B.T. 1984, Ap.J.Lett., **278**, L11.
	photometry, 10µm	Brown, R.H., Cruikshank, D.P., and Griep, D. 1975, ICARUS, **62**, 273.
Crommelin	photometry 1.25-20µm	Hanner, M.S., Knacke, R., Sekanina, Z., and Tokunaga, A.T. 1985, A&A, **152**, 177.
Churyumov-Gerasimenko	photometry 1.25-20µm vs. R. Multichannel spectrometer 8-13µm	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.
Halley	photometry 1.25-20µm vs. R.	Tokunaga, A.T., Golisch, W.F., Griep, D.M., Kaminski, C.D. and Hanner, M.S. 1986, A.J., **92**, 1183.
	photometry 2.2-20µm vs. R.	Hanner, M.S., Tokunaga, A.T., Golisch, W.F., Griep, D.M. and Kaminski, C.D. 1987, A&A, in press.

Halley (cont.)	multichannel spectrometer, 5-13μm	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, A&A, in press.
	multichannel spectrometer, 5-10μm.	Campins, H., Bregman, J.D., Witteborn, F.C., Wooden, D.H., Rank, D.M., Allamandola, L.J., Cohen, M. and Tielens, A.G.G.M. 1986, in Exploration of Halley's Comet, Proc. 20th ESLAB Symposium, ESA SP-250 II, 121.
	multichannel spectrometer, 16-30μm.	Herter, T., Gull, G.E., and Campins, H. 1986, in Exploration of Halley's Comet, Proc. 20th ESLAB Symposium, ESA SP-250 II, 117.
	photometry 1.25-20μm	Gehrz, R.D. and Ney, E.P. 1986, in Exploration of Halley's Comet, Proc. 20th ESLAB Symposium, ESA SP-250 II, 101.
	photometry 10μm	Russell, R.W., Lynch, D.K., Rudy, R.J., Rossano, G.S., Hackwell, J.A., and Campins, H.C. 1986, in Exploration of Halley's Comet, Proc. 20th ESLAB Symposium, ESA SP-250 II, 125.
	photometry 1.25-19μm vs. R	Green, S.F., McDonnell, J.A.M., Pankiwicz, G.S.A., and Zarnecki, J.C. 1986, in Exploration of Halley's Comet, Proc. 20th ESLAB Symposium, ESA SP-250 II, 81.