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CHAPTER 1

INFRARED OBSERVATIONS OF THE DUST COMA

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1.0 WHAT WE LEARNED FROM COMET HALLEY

The main infrared observational results were briefly reviewed at the start of the session. No attempt was made for completeness; instead the speakers (Bregman, Brooke, Campins, Encrenaz, Gehrz, Lynch, and Tokunaga) concentrated on the final results and the new questions they raised. These new results are summarized below. Further discussion of these results is given in the abstracts at the end of this report (with references to the primary publications).

All of these results have yet to be synthesized into a self-consistent picture of the dust grain composition, dust production history, outburst mechanisms, and composition of the nucleus. The workshop discussion was helpful in pointing out problems faced by theorists, such as data of variable quality, the lack of the proper theory for computing the scattering and emission of irregular particles, and in some cases the lack of optical constants of "realistic" materials. We may expect, however, that the gross spectral and dynamical properties of Comet Halley can be understood in time, even if the details of the observations and the theoretical calculations continue to vex us into the future.

SUMMARY OF NEW RESULTS

(Unless indicated, these results refer only to Comet Halley)

- New emission features ascribed to C-H vibrations in organic material were detected at 3.36 and 3.52μm by Vega IKS and subsequently observed out to r=2 AU post perihelion. Emission at 3.29μm, the position of the interstellar unidentified feature, may also be present.
- First cometary spectra at 5 - 8μm showed none of the expected organic features, but a possible emission feature at 6.8μm, which is attributed to carbonates.
- Structure (at least one sharp peak) was detected for the first time in the broad 10μm emission; this structure and shape is interpreted as indicating anhydrous crystalline olivine and pyroxene particles.
- New emission features were detected in the 16 - 68μm spectral region, at 28.4 and tentatively at 23.8, 34.5, and 45μm; these are possibly due to olivine.
- Changes in dust optical properties (polarization, color, temperature, silicate emission) were well documented and seem to be associated with outbursts.
- New infrared imaging techniques applied to Halley detected radial trends in the optical

properties of the coma dust.

Although this workshop concentrated on dust, there was some discussion of infrared observations of gaseous species. We point out the most significant discoveries in this area.

- The H_2O molecule was directly detected for the first time at 2.65μm and the ortho/para ratio measured.

- Vega IKS spectrometer shows evidence for emission by the following gases: H_2O, CO_2, CO, H_2CO, OCS, as well as the C-H features and possibly C≡N.

2.0 THE INFRARED OBSERVATIONS

2.1 Photometric Monitoring

Several observatories carried out regular monitoring programs of 1 - 20μm filter photometry. These data are valuable for defining the activity level and temporal changes in dust properties, as well as giving a photometric reference for the higher resolution spectral studies. The monitoring programs known to us are compiled in Table 1.1. For this purpose, a monitoring program is defined as at least four data sets taken in a consistent manner through standard infrared filters. A complete listing of infrared observations is available from the International Halley Watch (IHW) Infrared Net.

2.2 New Spectral Features

One of the most significant aspects of the Comet Halley observations was the detection of many new molecules, solid-state features, and new unidentified features. Table 1.2 gives a summary of these spectral features; for further information, refer to the abstracts and the references.

One of the primary observational difficulties was the limited opportunity to confirm the presence of new spectral features. This is most important for the features which are weak and difficult to identify. In spite of the best efforts, there are spectral features for which only a single observation is available or for which the existence of the feature remains uncertain because of possible instrumental effects. This is particularly true for spectral regions inaccessible from the ground. In such cases, the feature is indicated as "tentative" in the Table.

In the case of Comet Halley, it is difficult to be sure of the existence of some features as they may be (1) present only in Comet Halley and not in other comets; (2) present in comets generally, but variable; and (3) spurious. This underscores the importance of synoptic observations of comets and continued observations of more comets with adequate spectral resolution and signal to noise to observe rarely seen features. Whether the spectral features we see in Comet Halley are typical or not is not known at the present time (with the exception of the H_2O fluorescence emission).

The difficulties discussed so far should not obscure the fundamental discoveries obtained through infrared spectroscopy of Comets Halley and Wilson: (1) the observation of H_2O fluorescence for the first time, (2) the discovery of a hydrocarbon feature at 3.4μm, (3) the discovery of structure in the 10μm silicate feature, (4) the discovery of CO_2 at 4.3μm and possibly H_2CO at 3.5μm, and (5) the discovery of new emission features at 2.8 and 28.4μm in Comet Halley and at 12.2μm in Comet Wilson. These discoveries are a quantum leap in the number of spectral features observed and demonstrate the importance of infrared observations for cometary studies.

The 3.4μm feature is discussed in detail in Section 2.3. This feature probably arises

TABLE 1.1

HALLEY INFRARED PHOTOMETRIC MONITORING PROGRAMS

Telescope	Location	Field of View (arc sec)	Inclusive Dates	Filters	Ref.
0.76m O'Brien	U. Minn.	19.5	12 Dec 85– 6 May 86	V – 18.5 μm	Gehrz & Ney 1986
2.3m WIRO	U. Wyoming	5, 8	12 Jan 86 30 Apr 86	2.3 – 23 μm	Gehrz & Ney 1986
3.0m IRTF	Mauna Kea	7	18 Jan 85 10 Mar 87	1.2 – 20 μm	Tokunaga et al 1986
3.0m IRTF	Mauna Kea	7	16 Jan 86 5 Mar 86	2–20 μm 7.5–13 CVF	Campins & Ryan 1987
3.8m UKIRT	Mauna Kea	5	20 Dec 84 3 May 86	1.2 – 20 μm	Green et al 1986
1.5m Steward Observatory	Mt. Lemmon	15	8 Nov 85 13 Jan 86	2 – 13 μm	Lynch et al 1986
3.0m IRTF	Mauna Kea	8, 10	21 Sept 85 27 Apr 86	JHK polarimetry	Brooke et al 1986
1.3m KPNO	Kitt Peak	11, 15, 33	22 Nov 85 28 May 86	JHK polarimetry	Brooke et al 1986
1m ESO	La Silla	5–30	4 Nov 85 June 86	JHK LM	Bouchet et al 1987
0.75m SAAO	Sutherland South Africa	36	19 Oct 85 13 June 86	JHKL	Whitelock et al
1.25m Sternberg	Crimea USSR	12	2 Oct 85 21 June 86	JHK LM	Taranova & Shenavrin
1.5m TIRGO	Gornergrat Switzerland	10–25	14 Oct 85 23 Mar 86	JHK LM	Stanga et al 1986

from a hydrocarbon material, but the identification is uncertain (see Chapter 3). The 2.8μm feature is not securely identified, but OH infrared fluorescence, hydrated silicate emission, and LTE H_2O emission can be ruled out (Tokunaga *et al.*, 1987; Table 1.2). Similarly, only a tentative identification exists for the 28.4μm feature, but LTE H_2O and OH emission have been ruled out (Herter *et al.*, 1987).

The 2.63 and 2.7μm features were observed by Weaver *et al.* (1986). Mumma reported at this conference the likely existence of these features and that they may arise from clusters of molecules, although no firm identification could be made at this time.

2.3 The 3.4μm Hydrocarbon Feature

The most plausible identification of the 3.4μm emission feature (centered at 3.36μm) is that it arises from C-H molecular bonds, although the composition of the emitting material cannot be specified. The intensity of the 3.4μm feature was observed by the Vega spacecraft to vary with distance from the nucleus (within a few thousand km) in the same manner as a parent molecule (Combes *et al.*, 1986, Encrenaz *et al.*, this report). The feature-to-continuum ratio was found to be constant with distance from the nucleus from ground-based observations (Knacke *et al.*, 1986). A 3.29μm emission feature, associated with PAHs in the interstellar medium, may also have been detected (Baas *et al.*, 1986; Encrenaz *et al.* 1987).

Brooke reviewed the emission mechanism theories for the 3.4μm feature (Brooke and Knacke, Chapter 3; see also abstracts by Danks and Lambert, Encrenaz *et al.*, and Chyba and Sagan). One of the main conclusions is that the abundance of carbon in Comet Halley depends greatly on the assumed emission mechanism, from less than 1% to about 30% of H_2O. Thus it is crucial to understand the emission mechanism in order to understand the carbon budget of the comet.

A discussion of how to understand better the emission mechanism yielded the following observational approaches:

1) The further study of the 3.4 and 6-8μm spectral regions in bright comets should help to determine whether or not some of the C-H bonds are attached to PAHs, and whether another hydrocarbon feature can be observed in the 6-8μm region. This may lead to an understanding of whether the 3.4μm feature could arise from thermal emission or not. A detection of a longer wavelength hydrocarbon feature could also lead to an identification. It was suggested that a 6-8μm feature, if it exists, should be observed from as large a heliocentric distance as possible ($r > 2$ AU ?). This is desirable so as to avoid overwhelming the potentially weak hydrocarbon features by the strong thermal emission of the grains. Only comets as bright or brighter than the past Comet Halley apparition can be studied effectively with current instrumentation.

2) Study of the feature/continuum ratio vs. heliocentric distance. More complete data similar to that obtained by Knacke *et al.* (1986) and Baas *et al.* (1986) may help to distinguish more clearly whether or not the 3.4μm feature strength follows that of the continuum thermal emission, or is dependent on the solar flux. In such a study, repeated observations are required of both the feature and the thermal continuum to remove the effects of variability.

3) Measurement of the feature intensity vs. distance from the nucleus. The best study thus far comes from the Vega-IKS experiment. Additional work could determine with greater certainty whether or not the 3.4μm feature is always a primary substance, rather than a daughter product.

4) Further spectroscopy. The 3.4μm feature appears very similar in Comets Halley and Wilson, but is it the same in all comets? In addition, high-resolution and high signal-

to-noise observations are necessary. The minimum spectral resolution for useful work is 400, such as that obtained by Baas *et al.* (1986). The "ideal" spectral resolution is 2,000-3,000 with good signal to noise. In general, it is more important to achieve high- signal to noise rather than high-spectral resolution to aid in the identification.

We await the arrival of the next bright comet!

2.4 Airborne Observations of Comets Halley and Wilson

Because a significant fraction of the infrared spectrum is not available to ground-based telescopes, airborne infrared observations played a key role in the study of the dust in Comets Halley and Wilson. A coordinated effort aimed at obtaining the maximum possible spectral coverage of Comet Halley yielded excellent results. A more modest effort (because of the severe time constraints associated with new comets) aimed at Comet Wilson also proved very fruitful.

For convenience, we will divide the airborne observations into the four spectral regions covered by the instruments used. Following is a summary of the main results from each region.

The 5 to 9μm Region in Comet Halley

Spectrophotometry from 5 to 9μm (spectral resolution = 2%, see Fig. 1.4) was obtained from the Kuiper Airborne Observatory (KAO) on 12.1 Dec. 1985 and on 8.6 and 10.5 April 1986 (Campins *et al.*, 1986; Bregman *et al.*, 1987). Photometry was carried out from the Lear Jet Observatory (LJO) on 7.6, 8.6, 9.6 and 11.6 April 1986 (Russell *et al.*, 1986).

- Except for the possible detection of a feature at 6.8μm (also observed by the Vega IKS instrument (Encrenaz, this report) and tentatively attributed to carbonates) none of the features expected in this region were found. Analogies with interplanetary dust particles and circumstellar dust had suggested the presence of features at 6.2, 7.7 and 8.6μm (Campins *et al.*, 1986). Thus, any attempt to link the 3.4μm emission features to organic materials must explain the absence of these longer wavelength features.
- A new and unidentified feature observed to rise from 5.5 to 5.24μm (the shortest wavelength observed) is present in all but one of the Halley spectra, after normalization to a 325 K black body (Bregman *et al.*, 1987).
- The onset of a strong, broad silicate emission feature is observed, consistent with the emission observed in the 8 to 13μm spectrum obtained from the ground on 17.2 Dec (Bregman et al., 1987). The onset of the emission seems to occur at a shorter wavelength than previously believed, beginning between 7.5 and 8μm, depending on how the continuum is defined. The strength of the feature relative to the continuum was higher on 8 April than 10 April.
- The 5 - 7μm color temperature is significantly higher than an equilibrium black body, indicating the presence of small hot dust grains. This color temperature is higher than that observed at longer wavelengths, where the emission arises from larger, somewhat cooler grains (but still warmer than an equilibrium black body). This dependence of the color temperature on wavelength is the main reason why it is difficult to define the continuum under the broad silicate emission.
- Spatial variations in the color temperatures were found in April between the photocenter and other coma observations one beamwidth away.
- Temporal variability of the overall brightness equal to that described in Section 2.7 was observed between flights.

The 5 to 13μm Region in Comet Wilson

Spectrophotometry was obtained from the KAO on 23.6 and 25.6 April 1987 (Lynch *et al.*, this report). Preliminary results are:

- The observations are consistent with a weak silicate emission, apparently different from that in Comet Halley at the same heliocentric distance (1.2 AU).
- A new and unidentified feature was found at 12.2μm which has not been observed in any other astronomical source.
- The color temperatures from the 5 to 8μm region are very high, a behavior similar to that found in Comet Halley.
- No measurable short-term variability was displayed by this comet, in sharp contrast to Comet Halley.

The 16 to 30μm Region in Comet Halley

The Cornell University 16 to 30μm spectrometer (spectral resolution = 1%, see Fig. 1.1) was used from the KAO on 14.2 December 1985 (R=1.28 AU preperihelion; Herter *et al.*, 1987). Only one observation with this instrument was obtained, and hence no information on spatial or temporal variability is available.

- No strong, or sharply peaked, silicate emission feature was evident near 20μm. Without simultaneous data at shorter wavelengths it is difficult to know where to draw the continuum (particularly in light of the large brightness fluctuations observed on timescales shorter than a day); thus a broad, relatively weak feature cannot be ruled out.
- Excess emission in broad and narrow-band 20 μm photometry is clearly present when the comet was closer to the sun. Hence, the lack of an obvious feature in the 20μm airborne spectrum may be due to uncertainties in the level of the continuum and unfortunate timing. The 10μm silicate feature was clearly present, but still relatively weak, in filter photometry on 13.3 Dec (Tokunaga *et al.*, 1986).
- A new feature was found at 28.4μm. This finding has been confirmed in one of the 20 to 68μm unpublished spectra (Glaccum, *et al.*, this report). Theoretical models have ruled out LTE emission by OH and H_2O as the source of this feature (Herter *et al.*, 1987).
- Possible new features were observed at 23.8 (also observed in a 20-68 μm spectrum) and at 26.7μm. The 23.8, 28.4μm and two more features in the 20 to 68μm region (see below), have been tentatively identified with olivine particles.

The 20 to 68μm Region in Comet Halley

The NASA-Goddard spectrometer (spectral resolution = 2 to 3%, see Fig. 1.2) was flown on the KAO on 17.1 and 20.1 December 1985 and 15.6 and 17.7 April 1986 (Glaccum *et al.*, 1987).

- No strong features were found; however, a series of weak (7% above the continuum), but repeatable features have been found near 24, 28, 35, and 45μm, and tentatively identified with olivine particles, in agreement with conclusions obtained from the structure of the 10μm silicate feature (Table 1.2 and Glaccum *et al.*, this report). This identification suggests that, similarly to the 10μm region, there may be a broad (but much weaker) 20μm silicate feature with structure (narrower peaks) characteristic of olivine (see discussion in 2.5).

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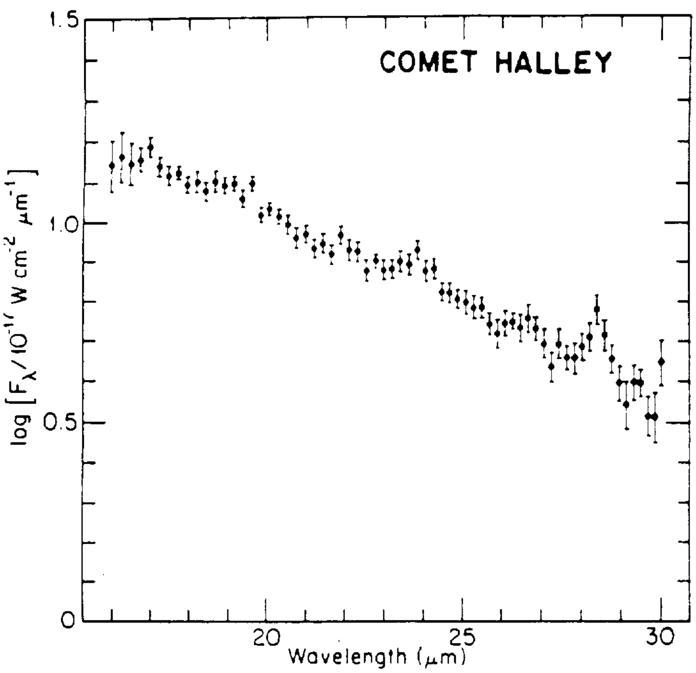

Figure 1.1 - The 16 to 30μm spectrum of Comet Halley (December 1985). A sharp new feature was discovered at 28.4μm and two ones at 23.8 and 26.7μm. The 23.8 and 28.4μm features have been tentatively identified with crystalline olivine (see Fig. 1.2). No strong, broad silicate emission is evident in this spectrum; however, without simultaneous data at shorter wavelengths it is difficult to know where to draw the continuum particularly in light of the large brightness fluctuations observed in Comet Halley on timescales shorter than a day. Figure adapted from Herter, Gull and Campins (1986).

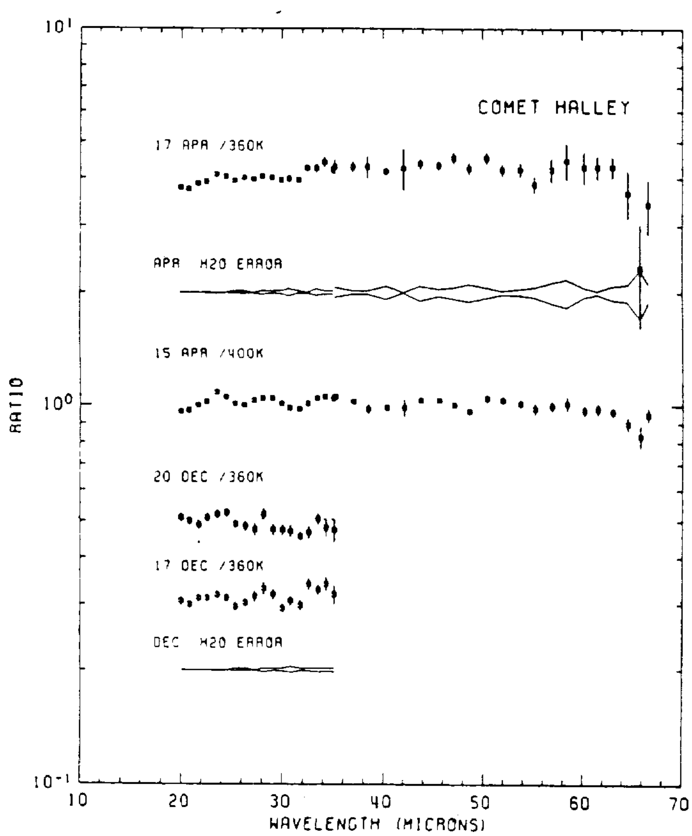

Figure 1.2 - The 20 to 36μm and 20 to 68μm spectra of Comet Halley (December 1985 and April 1986) relative to blackbody fits to the continuum. The emission features near 24 and 28μm discovered by Herter, Campins, and Gull (1987) are confirmed, and most clearly seen in the December 20, 1985, spectrum. These two features along with two more features peaking near 35 and 45 microns (in the April 15, 1986, spectrum) have been tentatively identified with crystalline olivine, in excellent agreement with the identification of the structure of the 10μm silicate emission (see Figs. 1.3 and 1.4). Also shown (solid lines labeled H_2O error) is the effect on the errors of a change of $\pm$20% in the ratio of boresight water vapor for observations of the comet and calibration stars. Figure adapted from Glaccum *et al.* (1986) and Glaccum *et al.*, this report.

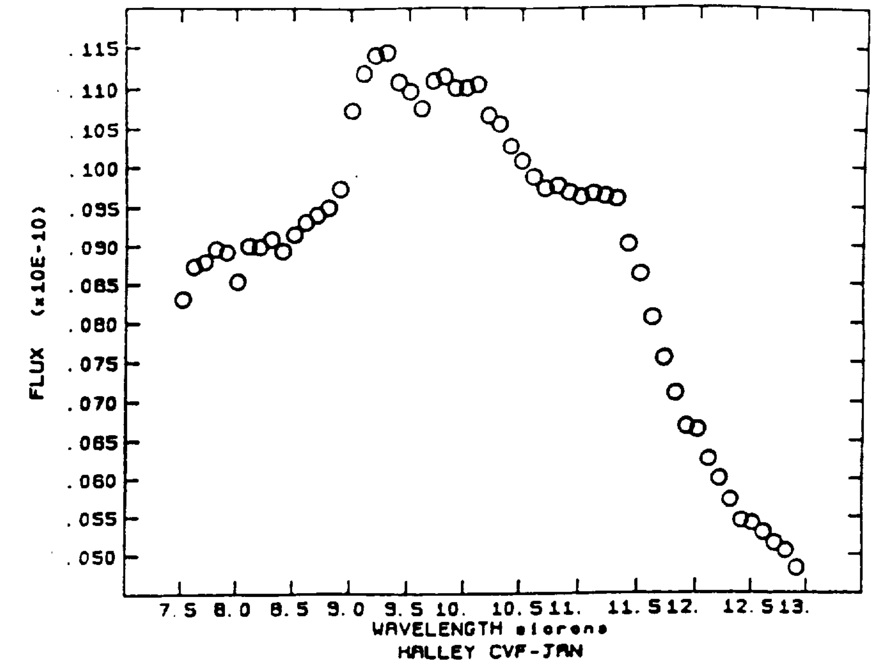

Figure 1.3 - The 7.5 to 13μm spectrum of Comet Halley obtained on 16.0 January 1986. The one sigma errors are smaller than the symbols except in the 7.5 to 8.0μm and 9.3 to 10.0μm regions where the errors can be several times the size of the symbols. The continuum is not well defined but can be approximated by a straight line joining the first and last data points. The flux is in units of Watts cm$^{-2}\mu$m^{-1} (from Campins and Ryan, this report).

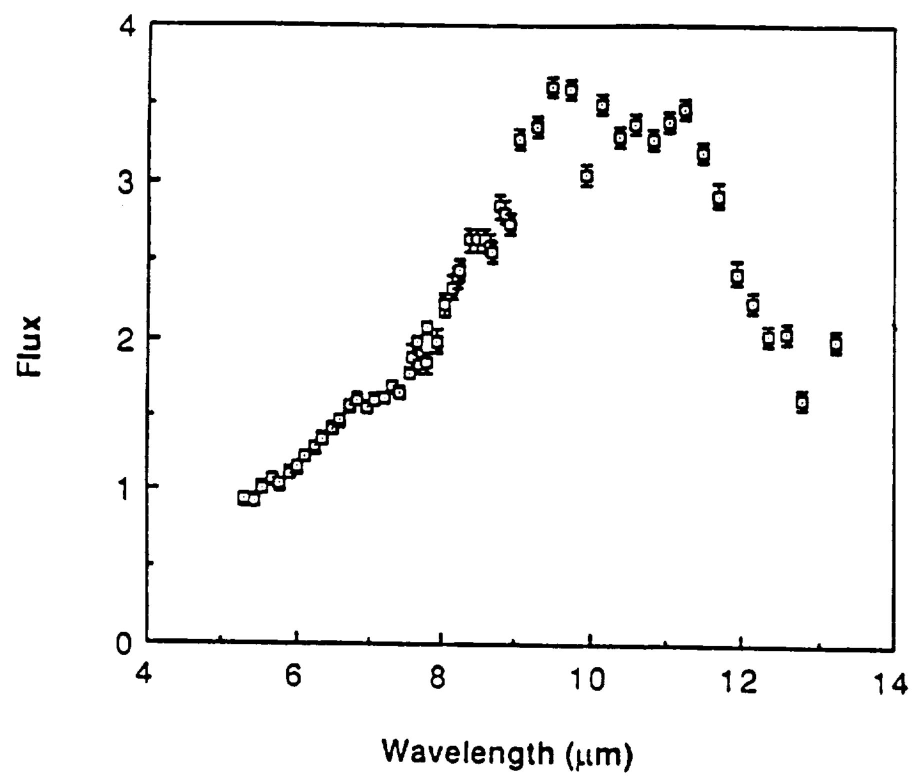

Figure 1.4 - The 5 to 13μm spectrum of Comet Halley obtained on 12.1 (8 to 13μm) and 17.2 (5 to 9μm) December 1985. The low datapoint at 9.7μm is due to a miscorrection for the terrestrial ozone. The flux is in units of 10^{-16} Watts cm$^{-2}\mu$m^{-1} (from Bregman *et al.*, 1987).

Table 1.2

Spectral Features Observed in Comets Halley and Wilson

Wavelength(μm)	Species	References	Remarks
1-2.5	CN,H_2O	25	
2.6, 2.7(?)	?	31, 40	Broad emission features
2.7(?)	H_2O gas	11, 14, 29, 40	Obs. in Halley & Wilson
$\approx$ 2.8	?	30, 39	Obs. in Halley & Wilson
3.0	H_2O ice	3, 11, 14, 38	Tentative
3.15	?	14	Tentative
3.29	PAHs(?)	1, 14	Tentative
3.36	CH features	1,11,12,13,14,23,27	Obs. in Halley & Wilson
3.52		39, 41	
3.6	H_2CO	11, 13, 14, 27	ID not confirmed
4.3	CO_2	11, 13, 14, 27	First detection
4.44	C N	14	Tentative
4.6	CO	11, 14, 27	Tentative
4.84	OCS	14	Tentative
5.2	?	6	Tentative
6.8	Carbonates	4, 6	Tentative
9.8, 10.5, 11.3	Silicates	4, 10, 14	Olivine and pyroxene? Variable
12.2	?	24	Observed in Wilson; tentative
$\approx$ 20	Silicates	15, 16, 22	Shape uncertain
23.8	Olivine?	16, 22	Tentative
26.7	?		Tenative
28.4	Olivine?	16, 22	Variable strength
34.5	Olivine?	16	Tentative
45	Olivine?	16	Tentative

- The continuum has been modeled and the derived particle-size distribution is consistent with that measured by the spacecraft.
- Temporal variability of the overall brightness was observed.
- No spatial variability of the color temperature was observed between the photocenter and observations one and two beamwidths away.

The 40 to 160μm Region of Comet Halley

Because of the rapidly dropping flux level with wavelength, this region could only be observed using broadband photometry, and hence there is information on the shape of the continuum but not on any spectral features. The University of Texas far-infrared photometer was used on the KAO on 15.7 and 16.7 March 1986 (Campins *et al.*, 1987b).

- Modeling of the shape of the continuum is consistent with the results obtained from the 20 to 68μm region.
- A color temperature gradient was found with the hottest point at the photocenter.
- Observations on two consecutive days show brightness variability of a factor of two; lower color temperatures were observed when the comet was fainter.

2.5 Silicate Features

Until recently, these features were the only solid state spectral features observed in comets and one of the few observational clues to the composition of cometary solids. The Comet Halley observations have shown these features to be more complex and more diagnostic of the dust's composition than previously believed.

Circumstellar and Interstellar Sources

A broad emission or absorption feature which peaks near 10μm and is generally associated with oxygen-rich stars has been attributed to the stretching vibration of Si-O bonds in silicate grains. This identification is strengthened by the presence of a feature in the 16 to 24μm region produced by the O-Si-O bending mode. Because of its width and lack of a sharply defined structure (peaks), the 10μm feature has been generally explained as due to amorphous silicate grains, and hence, not very diagnostic of the specific type of silicate producing the feature.

Previous Comets

There is a large body of filter photometry showing that the 10μm feature is present in most (but not all) comets within 1 AU of the sun (Ney 1982 and references therein).

Before Comet Halley it had been thought that the cometary 10μm feature was similar in shape to the interstellar feature and thus also due to amorphous grains. Prior to Halley, few spectra of the cometary silicate feature had been obtained; the one with the best spectral resolution and signal to noise was of Comet Kohoutek (Merrill, 1974). This spectrum showed a broad, structureless feature; thus, it was thought that comets must also have amorphous silicates. A number of other spectra taken of comets beyond 1 AU from the sun (Churyumov-Gerasimenko, IRAS-Araki- Alcock, Grigg-Skjellerup and Wilson) are consistent with either no emission feature or a very weak structureless one. On the other hand, interplanetary dust particles (IDPs), which are believed to be mostly of cometary origin, show clear structure in the 10μm region due to the presence of crystalline olivine, pyroxene and hydrated silicates (Sandford and Walker, 1985; Sandford, Chapter 3).

No published spectra of the 20μm region of comets existed before Comet Halley's apparition. The presence of this feature in comets was determined from filter photometry (Ney, 1982, Rieke and Lee, 1974).

Halley

a) The 10μm Feature

There are four published spectra of the 10μm region of Comet Halley (Bouchet *et al.*, 1987; Bregman, *et al.*, 1987; Campins and Ryan, this report; Encrenaz, this report). All these spectra show some structure in the band and are roughly consistent with each other. The structure is clearest in the spectra of Bregman *et al.* and Campins and Ryan which are shown in Figures 1.1 and 1.2. These spectra show a clear peak near 11.3μm with possible structure between 9 and 10μm which is difficult to define due to the presence of the telluric ozone absorption. The width and structure observed in Halley's 10μm emission has been reproduced using a sample of IDP spectra (Sandford, Chapter 3). A good fit requires a combination of anhydrous, crystalline olivine and pyroxene particles. This is radically different from the case of Comet Kohoutek (Sandford and Walker, 1985) and in excellent agreement with the results from the Vega and Giotto mass spectrometer observations (Brownlee, Chapter 3) which suggest, based on a comparison with the mass spectra of meteoritic particles, that the Si-bearing particles are indeed anhydrous.

Comet Halley's silicate particles are, thus, different from those in Comet Kohoutek (at least based on the comparison between several spectra of Halley taken at different heliocentric distances, ranging from 0.8 to 1.2 AU, and a single spectrum of Kohoutek, taken at 0.3 AU) and from those so far observed in interstellar and circumstellar dust. However, they appear to be similar to the anhydrous IDPs studied in the laboratory.

b) The 20μm Feature

Evidence for the presence of this feature in Comet Halley when the comet was within 1 AU of the sun comes from filter photometry which shows this spectral region to be significantly above extrapolations of the continuum at shorter wavelengths. The only published spectrum of any comet in this region is discussed in Section 2.4. Although no evidence was found for a strong 20μm silicate emission at the time the spectrum was obtained (heliocentric distance = 1.3 AU), four weak emissions observed near 24, 28, 35, and 45μm have been tentatively identified with olivine, in agreement with the same identification in the 10μm spectrum.

Spatial and Temporal Variations

The 10 and 20μm emission features were observed to have temporal variability on timescales as short as a few hours, and spatial variability in the coma. This variability makes very difficult the combination of different data sets (taken at different times or with different apertures). More detailed discussions of these variations are given in Sections 2.6 and 2.7; however, the mechanisms for the observed variability are not understood.

Recommendations for Observations of Future Bright Comets

It is clear from the case of Comet Halley that observations of the silicate features are potentially very diagnostic of the composition of the dust. Furthermore, observations of other comets are essential to determine how typical (or unusual) the silicates in Comet Halley are. In order to maximize the effectiveness of future observations one must consider the following recommendations:

a) Comets at heliocentric distances smaller than 1 AU are most likely to show well-developed 10 and 20μm features.

b) Simultaneous observations of the 10 and 20μm regions as well as of the continuum (shortward of 7.5μm) are essential for the determination of the relative and absolute strengths of these features.

c) Observations at a variety of heliocentric distances are necessary to de-couple the behavior of the feature from that of the continuum.

2.6 Spatial Variations

Two-dimensional detector arrays at infrared wavelengths are coming into use, and several groups obtained infrared images of Halley's dust coma. The importance of these arrays for comet study lies in their ability to image the dust coma relatively quickly at several wavelengths, in order to map spatial variations in the optical properties of the grains.

JHK Colors

Rieke and Campins (1987) reported on J,H,K images taken 3.5 Nov. 1985 which show well-defined J-H and H-K color gradients within 7,000 km of the nucleus, with bluest colors at the photocenter. Radial brightness gradients were steeper than the 1/d expected for a steady-state isotropic outflow of dust, where "d" is the projected distance from the nucleus. These authors pointed out that both of these phenomena are consistent with a coma of volatile (dirty ice) grains; however, other explanations, such as recent emission of small (Rayleigh scattering) grains, are also possible.

Albedo Maps

Thermal images were combined with nearly simultaneous CCD visible images to obtain albedo maps. A map obtained on 18.4 Nov. 1985 shows an increase in albedo away from the nucleus, except in the anti-solar direction where the albedo decreases (Hammel *et al.*, 1987). A similar spatial structure was found in an albedo map obtained for Comet Giacobini-Zinner on 4.4 Aug. 1985 (Telesco *et al.*, 1986). However, the absolute value of the albedo in Comet Halley was about three times greater than that in Comet GZ, attributed to the fact that Halley was near opposition (phase angle 2° on 18.4 Nov). This interpretation is supported by the albedo map of Halley obtained on 13.7 March 1986, which shows the absolute level of the albedo to be roughly equal to that of Comet GZ when observed at a similar phase angle (Hayward *et al.*, 1987b).

Spatial Structure

Both thermal images and single-detector maps obtained in early 1986 show sunward fans and radial surface brightness profiles more complex than the "canonical" 1/d , as would be expected for patterns of variable dust emission. (Campins and Ryan, this report; Campins *et al.*, 1987b; Hayward *et al.*, 1987; Hanner *et al.*, 1987).

Silicate Features

The strengths of the 10 and 20μm silicate features, and their ratio, were observed to vary with location in the coma. The features were usually – but not always – strongest at the photocenter (Campins and Ryan, this report; Campins *et al.*, 1987b; Hanner *et al.*, 1987b).

Polarimetric Images

Broad-band polarimetric images taken on 5.7 and 7.7 Jan 1986 show maximum polarization in dust jets and not at the photocenter (Eaton *et al.*, this report).

2.7 Temporal Variations

The comet showed frequent and possibly periodic infrared brightness variations. On timescales shorter than or equal to a day, brightness changes greater than a factor of 3 were observed. Because of their frequency and regularity, these brightness variations may not fit the classical definition of outbursts. However, for lack of a better term, we will refer to them as outbursts.

JHK - Color Correlation with Outbursts

A possible correlation between bluer J-H colors and brightness maxima was reported by Hanner. It is interesting to note that in the spatial trends discussed earlier, the bluest J-H and H-K were found on the brightest point in the coma.

Tokunaga (this report) reports systematically bluer JHK colors after July 1986 in the IRTF monitoring data and suggests that the composition of the grains may have changed.

Albedo Changes During Outbursts

A sudden drop in the 2.2μm (reflected light) brightness of Comet Halley was observed within a few hours; the 10μm brightness stayed roughly constant during this period, indicating a sudden change in the effective albedo of the coma (Lynch *et al.* 1986).

A correlation between higher albedo and brightness peaks is reported by Green *et al.* (this report), Gehrz and Ney (1986), and Tokunaga *et al.* (1986).

Variability in the Silicate Emission

Gehrz and Ney (1986) report the disappearance and reappearance of the 10 and 20μm silicate emission features on a timescale of a few days. (See also Green *et al.*, 1986 and Hanner *et al.*, 1987b).

A change in the shape and strength of the 10μm emission on a timescale of three hours on 3.8 March 1986 has been observed (Campins and Ryan, this report).

Broad- and narrow-band photometry show stronger 10 and 20μm features when the comet was brighter (Hanner *et al.*, 1987b; Campins Ryan, this report).

High Temperature Correlation with Outbursts

A higher color temperature, based on the 40-160μm photometry, was found when the comet was brightest (Campins *et al.*, 1987a).

Further analysis is necessary to determine if a brightness – color temperature correlation is present in the filter photometry sets of Campins and Ryan, Gehrz and Ney and Tokunaga *et al.*

Polarization Increases During Outbursts

Mukai (this report) reported increases in the polarization during brightness maxima observed by the Suisei spacecraft. He has modeled and interpreted these as an increase in the abundance of small particles.

To summarize, there is evidence that, at times of enhanced dust production, the J-H color may be bluer, the 1 - 2μm albedo increases, silicate features are stronger, and the polarization is higher. All of these optical properties are consistent with a shift in the observed size distribution toward smaller grain sizes at times of dust outbursts, although changes in the composition of the dust are not ruled out.

2.8 Problems in Comparing Separate Data Sets

In order to obtain the most complete picture of the infrared activity of Comet Halley, it is necessary to combine data sets of different observers. Most data sets will be eventually found in the archives of the IHW (and for this reason all observers are encouraged to submit Comet Halley data to the IHW).

However, there are significant problems in comparing such data sets. As an illustration of the difficulties, consider the problems in the straightforward case of comparing two photometric data sets. It is first necessary to resolve differences in the photometric system: standard star magnitudes, and flux densities, beam size, filter sets, effective wavelengths, and sky chop amplitude. An additional major complication is that even with a resolution of such problems, the variability of the comet may preclude a direct comparison unless it is known that the comet was quiescent at the time the comparison is made.

Nevertheless, there are cases where the comparing of data sets is important. Examples include the joining of data sets (1) to construct the infrared photometric history of the comet, (2) to obtain more complete wavelength coverage, (3) to search for color or color temperature variations during outbursts, and (4) to confirm the detections of spectral features.

In view of the relatively subtle problems involved with the comparing of data sets, such work should be accomplished by the observers themselves whenever it is possible. In general it will not be meaningful to compare data sets taken directly from the IHW archive without considering in detail the differences in the photometric system, method of data reduction, and considering the possibility of variability.

From the above considerations, it is highly desirable that the comparing of data sets be undertaken as soon as possible, so that the primary sources of data can be consulted with the benefit of fresh memories.

2.9 Polarization

The near-infrared polarization of Halley is similar to the visible polarization in this and other comets in showing a negative branch of a few percent at small phase angles, a neutral point at $\theta = 20$ deg, and an approximately linear rise toward larger phase angles (Brooke *et al.*, abstract this report). However, the polarization increases with wavelength at large phase angles, contrary to the available polarimetry of asteroids, interplanetary dust, and Comet West. Visible polarization of Halley also shows a slight increase with wavelength, from 0.365 to $1 \mu m$ (Mukai, *et al.* 1986). Mukai also reported an increase in polarization associated with brightness maxima (outbursts). Polarimetric images show maximum polarization in dust jets, not at the photocenter (Eaton *et al.*, this report).

The interpretation of these results in terms of physical characteristics and composition of the particles is complicated because Mie theory calculations are valid only for smooth perfect spheres. Laboratory experiments and theoretical studies of rough particles should help in the interpretation of the observations (see Chapter 2).

2.10 Comet Wilson

Comet Wilson provided the opportunity to compare a new comet with Halley. Already active at a heliocentric distance greater than 3 AU, it was predicted to be as bright as Halley when it reached perihelion at 1.2 AU in April 1987. The comet did not quite live up to the predictions, and its southern declination and small elongation made observations difficult. Thus, fewer observations than originally anticipated were obtained. A log of observations of Comet Wilson, compiled by D. Lynch, is presented in Table 1.3. These include four KAO flights. The preliminary infrared results are summarized here:

A new spectral feature was discovered at 12.2μm (FWHM = 0.2 μm). This emission was present in all the KAO spectra on 23.6 and 25.6 April 1987 (Lynch *et al.*, this report).

A 3.36μm feature similar to that observed in Comet Halley was detected on 24 May 1987 (Brooke *et al.*, 1987).

There was no evidence for a strong 10μm silicate emission in early March (Bregman *et al.*, this report), late April (Lynch *et al.*, this volume) and late May (Hanner and Newburn, this report). The KAO spectra are consistent with a weak 10-μm silicate emission.

No significant day-to-day variability was found in thermal infrared images obtained on 13, 14, and 15 March 1987 (Campins *et al.*, 1987c).

The emission from gaseous H_2O at 2.65μm was also detected in this comet using the KAO. The ortho/para ratio in the H_2O gas was measured (Mumma *et al.*, this report).

3.0 RECOMMENDATIONS

Interpreting Halley Observations

1) Observers should clearly state standard star magnitudes, flux calibration, filter- effective wavelength, beam size, and sky-chop amplitude and direction when reporting observations. Comments on the weather or other factors affecting data quality are also helpful. Because the comet varied on timescales of a few hours, the time of the observations should be given.

2) Modelers should contact observers to assess potential problems with data, such as the reality of features, reproducibility, unconfirmed results, etc. This is an important "no-cost" mechanism to enhance the quality of interpreted results.

Observations of Future Comets

1) The 10 and 20μm silicate features need to be observed with good temporal coverage, to ascertain whether spectral structure indicative of crystalline grains is present for other comets and to document changes with heliocentric distance (i.e., with grain temperature). The 10μm region can be observed from the ground with either circular variable filters (CVF) or spectrometers at resolution of $\sim$ 1%, while the 20μm region requires airborne observations. Ground-based photometry indicates that the 20μm emission is strongest when comets are less than 1 AU from the sun.

2) Basic photometric monitoring is essential to define the thermal emission continuum and its variability. This can be done with intermediate- sized telescopes ($\sim$1 m), ideally telescope(s) dedicated for that purpose. The goal is to obtain uniform, moderate- to high-time resolution coverage. The broad-band spectral energy distribution allows the grain size distribution and the total cross section of emitting grains to be estimated.

3) Correlations between the 3.4, 10, and 20μm emission features need to be established with simultaneous observations. Coordinated observations among telescopes is required, as single telescopes cannot be expected to have all the instrumentation or to undertake observations at all of these wavelengths simultaneously (variations on time scales of a few hours can be expected).

4) Better spectral resolution of the broad-emission features at 3.4 and 10μm is required.

The continuum must be measured as well as possible.

5) Complete 5 - 13μm spectra and/or both 10 and 20μm spectra should be obtained during a KAO flight, in order to define the continuum level and to correlate spectral features. Lack of such coverage complicates the interpretation of Halley spectra.

6) More airborne data are required to confirm the presence of the 5.2, 26.7, 34.5, and 45μm emission features in comets. Additional laboratory work is needed to help identify these features.

7) A higher priority should be given to simultaneous airborne and ground-based data-taking. Some of the important airborne data on Comet Halley did not have corresponding ground-based data taken at the same time. In practice, this has been difficult to achieve because of the inevitable changes in flight schedules versus the long-lead time for scheduling observations at major telecopes. Coordinated KAO and Lear jet flights would be valuable for observing two spectral regions simultaneously.

8) There is a need for ground-based and airborne instrumentation which can observe more than one feature at a time (i.e., 3.4 and 10μm, or 10 and 20μm).

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COMET WILSON WORLD-WIDE OBSERVATION LOG

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The following is an abbreviated list of observations of Comet Wilson compiled up through January 20, 1988. The purpose is to allow people working on Comet Wilson to make contact with other observers who may have supporting data. No claim of completeness is made. More information can be obtained by contacting the observers noted. For brevity, only the name of the observing team leader or person reporting the observations is listed. Visual magnitude estimates can be obtained from the IAU circulars. A four-digit number in brackets (e.g., [4241] refers to the IAU circular reporting the observations. UT may be rounded to the nearest 0.1 day.

Observers are encouraged to send a brief summary of their observations to the author for inclusion in future editions of this log. Information can be sent to the above address or to DIRAC2::LYNCH on the SPAN network.

TABLE 1.3

DATE (UT)	Type of Observation		Observer
1986			
Aug 4-6	Palomar 1.2 m Schmidt - DISCOVERY	[4241]	C. Wilson
	Precise Positions		various
Aug 6-10	Precise Positions	[4243]	various
Aug 25-31	Nancay 1667 MHz OH		E. Gerard
Sept 2.3	LPL Catalina 1.5 m 300-930 nm spectra	[4253]	S. Larson
Sept 3.3	"		"
Sept 5.0-5.3	IUE 195-340 nm		P. Feldman
Sept 6.3	IRTF 10.8 μm bolometer array	[4258]	R. Decher
Oct 8.9-9.2	IUE 115-340 nm		P. Feldman
Oct 10-18	Nancay 1667 MHz OH	[4271]	E. Gerard
Oct 31.5	KPNO 2.1 m CCD R filter images		K. Meech
Nov 6-8	Nancay 1667 MHz OH	[4271]	E. Gerard
Nov 11-12	"	[4271]	"
Nov 16.8-17.1	IUE 115-340 nm		P. Feldman
1987			
Feb 6-7	VLA OH emission	[4314]	P. Palmer
Mar 13.8	IRTF 10.8 μm imaging		H. Campins
Mar 14.5-21.8	Pioneer Venus UV spectrometer		I. Stewart
Mar 14.8	IRTF 10.8 μm imaging		H. Campins
Mar 15.8	IRTF 10.8 μm imaging		H. Campins
Mar 17.1-19.8	Pioneer Venus UV spectrometer image		I. Stewart
Mar 17.7	Lick 1 m, 8 - 14 μm CVF spectra		J. Bregman
Mar 30.8- May 2.8	Pioneer Venus UV spectrometer		I. Stewart
Mar 28.8-29.1	IUE 115-340 nm		P. Feldman
Mar 29.8	UK Schmidt J plate 20^m	[4372]	C. Humphries
Apr 3.7-4.7	IUE 115-340 nm		P. Feldman
Apr 10.7-11.4	"		"

Apr 12.7	KAO 1.5 - 3.0 µm FTS	[4403]	H. Larson
Apr 14.7	"		"
Apr 16	CTIO 0.6 m photometry/molecules	[4371/2]	J. Ducati
Apr 17.7	KAO 1.5 - 3.0 µm FTS	[4403]	H. Larson
Apr 18	CTIO 0.6 m photometry/molecules	[4371/2]	J. Ducati
Apr 19	"		"
Apr 22.9	IUE 115-340 nm		P. Feldman
Apr 23.4	CTIO .6 m photometry/molecules	[4375]	J. Ducati
Apr 23.6	KAO 5.2 - 13 µm array spectra		D. Lynch
Apr 24.4	CTIO 1.5 Schmidt IIIa-J		K. Meech
Apr 24.4	CTIO .6 m photometry	[4375]	J. Ducati
Apr 25.4	"		"
Apr 25.6	KAO 5.2 - 13 µm array spectra		D. Lynch
Apr 26.4	CTIO 1.5 Schmidt IIIa-J		K. Meech
Apr 27.4	" IIa-O		"
Apr 27.4	El Leoncito 0.8 m CCD NB filters		P. Bernhardt
Apr 28.3	" 0.5 m " "	H_2O^+	"
Apr 28.4	Siding Spring 2.3 m CCD images		T. Rettig
Apr 29.3	El Leoncito 0.3 m CCD NB filters	CO^+	P. Bernhardt
Apr 29.4	" 0.5 m " "	CO^+	"
Apr 30.4	Siding Spring 2.3 m CCD images		T. Rettig
Apr 30.5	Siding Spring 2.3 m CCD spectra 380-700 nm		T. Rettig
May 1.2	El Leoncito 0.5 m CCD NB filters	H_2O^+	P. Bernhardt
May 2.0	CTIO 1.5 m Many short N/B CCD images		K. Meech
May 2.5	Siding spring 2.3 m CCD images		T. Rettig
May 3.3	El Leoncito 0.5 m CCD NB filters	H_2O^+	P. Bernhardt
May 4.2	" 0.5 m " "	H_2O^+	"
May 4.17	U. Toronto/Las Campanas photo 103a-O 5^m		C. Aikman
May 4.38	CTIO Schmidt 103a-0 10^m		A. Gomez
May 4.5	Siding springs 2.3 m CCD images		T. Rettig
May 4.5	Siding spring 2.3 m CCD spectra 380-700 nm		T. Rettig
May 5.15	U. Toronto/Las Campanas photo IIa-O, 098 5^m		C. Aikman
May 5.4	Siding Springs 2.3 m CCD spectra 380-700 nm		T. Rettig
May 5.5	Siding Spring 2.3 m CCD images		T. Rettig
May 5.6-6.0	IUE 115-340 nm		P. Feldman
May 6.3-7.0	"		P. Feldman
May 6.5	Siding Springs 2.3 m CD images		T. Rettig
May 7.4	AAO 3.9 m CCD spectra 390-690 nm		T. Rettig
May 8.04	U. Toronto/Las Campanas photo IIIa-J 5^m		C. Aikman
May 9.1	U. Toronto/Las Campanas photo IIIa-J, 098 5^m		C. Aikman
May 10.5	" IIIa-J, 098		"
May 10.5	AAO 3.9 m IPCS spectra 370-620 nm		T. Rettig
May 12.6-27.0	IUE 115-340		P. Feldman
May 16.1	CTIO 0.6 m NB photometry/308-700 nm		W. Osborn
May 20.0	"		"
May 21.0	"		"
May 24	IRTF 2.8 - 3.4 µm spectra	[4399]	T. Brooke
May 26.6-27.0	IUE 115-340 nm		P. Feldman
May 29.2	IRTF photometry M,N,8.7,10.3,12.5 µm		M. Hanner
Jun 1.2	" M,N,7.8,8.7,10.3,11.6,12.5 µm		"
Jun 1.2	" J,H,K,L		"
Jun 2.2	" N,Q,18 µm		
Jun 8.5-8.9	IUE 115-340 nm		P. Feldman

Jun 16.8	IRAM 30 m HCN J-1-0 88.6 GHz	[4411]	J. Crovisier
Jun 17.7	"		"
Jun 18.7	"		"
Jun 19.7	"		"
Nov	CCD Images at R		K. Meech
<u>1988</u>			
Jan 10.5	IRTF Photometry N, 18 μm		M. Hanner
Jan 11.5	IRTF Photometry J, H, K		"
Jan 12.5	IRTF Photometry N, 18 μm		"
Jan 13.5	IRTF Photometry N, 18 μm		"
Jan 14.5	IRTF Photometry J, H, K		"