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INFRARED OBSERVATIONS OF COMETARY SOLIDS

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INFRARED OBSERVATIONS OF COMETARY SOLIDS

by

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As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Humberto Campins Camejo

entitled Infrared Observations of Cometary Solids

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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ABSTRACT

Infrared photometry has been used to determine the physical characteristics of cometary solids. Observations were made of the reflected and thermal parts of the spectra of seven comets. Two of these comets, Bowell and West, were nonperiodic; the other five, Chernyhk, Encke, Kearns-Kwee, Stephan-Oterma, and Tuttle, were periodic.

Observations in the 3 μm region of the spectrum of Comet Bowell provide the first direct evidence for the presence of H_2O ice in a comet. This detection represents one of the strongest possible confirmations of Whipple's (1950) icy conglomerate model of cometary nuclei. The observations of the periodic comets have yielded the following picture of the dust in this type of objects: grains with a size distribution ranging from about 0.3 μm to 10 μm, and peaking around a few microns. These grains were made up of at least two components, a silicate material and an absorbing material. These characteristics are remarkably similar to those of the dust in nonperiodic comets. This indicates that the type of dust a comet ejects does not change with age, and supports the absence of large scale differentiation in cometary nuclei. Comet West is the first case of a splitting comet in which the fragments were observed to have differences in their dusty component. These observations suggest that the nucleus of this comet did not have

an "onion skin" or layered structure but rather had pockets containing dust grains with different size distributions.

Based on the results presented, the relation between cometary and interstellar dust, and the origin of comets are discussed.

CHAPTER 1

INTRODUCTION

Even the most primitive man must have had a good awareness of the sky; daily and seasonal changes were recognized by very early societies, as is evident in archeoastronomical findings. The apparition of a bright comet must have caused great commotion among primitive people; it is easy to imagine how they may have viewed the comet as an omen for whatever important event had occurred while it was visible.

Somehow, comets became a bad omen, and although their name in greek means "long-haired one", the ancient greeks considered them to be a signal of disaster or drought and believed them to be atmospheric phenomena and not a part of the "perfect" heavens. This view was fanatically defended through the Middle Ages. It was not until Tycho Brahe observed a bright comet in 1577 that it was established that they were further away than the moon, but their motion was still not understood. It was Edmund Halley (whose last name rhymes with alley), who, based on the newly invented newtonian mechanics, determined that the great comet of 1680 followed an elliptical orbit around the sun which brought it back every 75 or 76 years. Today, although we know more about comets, they are far from being well understood and are still feared by many.

The study of comets is of great importance to our understanding not only of the solar system but of other astrophysical environments like the interstellar and circumstellar medium. In the solar system, they are believed to be the most primitive material, Delsemme (1977) argues that they are less depleted in H, C, N, and O than even the most primitive meteorites; furthermore they are believed to have remained at temperatures lower than 150 K since their formation. Comets have been linked to many current solar system problems: 1) Brownlee (1978) concludes that most of the interplanetary dust particles collected from the upper atmosphere are of cometary origin; 2) Sill and Wilkening (1978) suggest that early bombardment by cometary bodies may have been the source of the atmospheres of the terrestrial planets; 3) Shoemaker et al. (1979) and Kresak (1979) propose extinct cometary nuclei as one possible source of earth-crossing asteroids. Cometary dust exhibits a strong resemblance to interstellar and circumstellar dust (Ney 1977), however, comets can be studied in more detail because their reflected light and thermal emission can be seen uncontaminated by the direct light of the illuminating star, in addition, a comet coma is at a single and known distance from the sun, whereas circumstellar dust shells contain dust particles at different distances from their stars and are by necessity observed in the presence of the direct starlight. Some (i.e., Greenberg 1982) consider comets as an intermediate phase between interstellar matter and more processed but still primitive solar system materials like CI carbonaceous chondrites.

Structure of the Nucleus and Physical Processes Around It

Structure and Composition

In 1950 Whipple proposed the icy conglomerate model of the cometary nucleus to explain the nongravitational effects in the orbits of periodic comets Encke, D'Arrest, and Wolf I; he further developed this model in a subsequent paper (1951). According to it, the comet nucleus is an aggregate of a volatile fraction composed of ices such as H_2O, NH_3, CH_4, CO_2 or CO and a nonvolatile component in the form of fine dust. This model replaces the sandbank hypothesis, wherein the nucleus was thought of as a diffuse cloud of small particles traveling together. Since its publication the icy comglomerate model has become generally accepted. A detailed analysis of the two models which offers strong support to the icy conglomerate structure has been given by Whipple (1964).

The degree to which cometary nuclei are undifferentiated is not completely clear; however, several circumnstantial arguments seem in favor of undifferentiated nuclei. The basic idea is that, if cometary nuclei were radially differentiated, the decay of their outer layers with aging or the splitting of their nucleus would eventually produce observable changes (Delsemme, 1982). The following arguments favor the undifferentiated nucleus:

1) The dust to gas ratio determined from the spectrum of 85 Comets by Donn (1977) does not seem to be influenced by aging.

2) The gaseous emission spectra of new and periodic (old) comets seems to be remarkably similar in the visual and ultraviolet (A'Hearn and Millis 1980; Feldman 1982).

3) Both the long and short period comets fragment at the same rate, about 3% per passage (Pitlich 1971; Kresak 1981; Stephanik 1966; Sekanina 1982).

This does not imply the absence of differences among comets, but that these differences do not change with aging. It has been suggested that exposure to galactic cosmic rays may change the composition of the outer layers of comets in the Oort Cloud. Donn (1976) suggests that the surface ice will tend to polymerise, forming less volatile substances. Whipple (1977), on the other hand, proposes that an outer layer rich in free radicals will exist as a result of cosmic ray exposure leading to reactions at lower temperatures. This may explain the large fraction of new or very young comets which have large perihelion distances but are particularly bright (one example being Comet Bowell 1980b). In Chapter 5 the implications of the observations presented in this work on structure of cometary nuclei will be discussed.

Sublimation of the Ices

In a comet nucleus the sublimation of the ices controls the ejection of gases and solids into the coma and tail. In order to model this sublimation, one must determine the temperature of the nuclear ices and the gas production rate.

In order to estimate the temperature of the nuclear ices the energy balance equation can be solved. In its simplest form it can be written as follows:

$$\frac{1}{4}\frac{F_o}{r^2}(1 - A_o) = (1 - A_{IR})\,ST^4 + Z(T)L(T) + \text{heat conduction} \quad (1)$$

where the 1/4 is the ratio of cross section to surface area of the nucleus, r is the heliocentric distance, F_0 is the solar flux at 1 AU, A_0 and A_{IR} are the nuclear albedos respectively in the visible and the infrared, s is the Stephan-Boltzman constant, T is the surface temperature, Z the production rate of gas in molecules cm^{-2} sec^{-1}, L is the latent heat per molecule for the vaporization of the snows. The heat conduction into the interior of the nucleus is considered negligible (Fernandez and Jockers 1982).

In order to determine the gas production rate Delsemme and Swings (1952) have shown that:

$$Z = p(2\pi mkT)^{-1/2} \quad (2)$$

where p is the pressure, m is the molecular mass to the gas and k is the Boltzmann constant. Solving Equations 1 and 2 by successive approximations for a snow of specified nature gives Z and T.

If one assumes that the visible light emitted by the coma (i.e., mainly C_2 emission) is proportional to the number of (invisible) parent molecules, one can compare the production rates observed to those generated using Equations 1 and 2. This technique has been successful in predicting the order of magnitude of the total production rate of gases in a few comets, mainly in cases where water is believed to have controlled the sublimation of the nucleus (Delsemme 1981). For instance, the estimates given by Delsemme (1966) are consistent with the production rates of H and OH measured later from space observations of bright comets.

As we can see from Equations 1 and 2 the temperatures and production rates depend (not very strongly, fortunately) on the choice of albedos. A large albedo (0.6) has been assumed for these calculations; however, recent evidence (Belton and Butcher 1982; Campins et al.1982a) indicates that the albedo of the nuclear ices may be as low as about 0.05. To date, uncertainties in the models and observations have made detailed comparisons difficult; however, any future refinements of the sublimation models have to take the darkness of the nucleus into account.

The nongravitational forces arise from the jet reaction produced by the subliming ices of the nucleus, as first pointed out by Whipple (1950). Marsden, Sekanina, and Yeomans (1973) have found the nongravitational effect in the motion of several other comets, and they can best explain it if water ice is assumed to be their major component.

The sublimation model described above, confirmed by brightness laws and by nongravitational force laws, strongly suggests that the sublimation of water ice controls the sublimation rate of many comets, probably including all short period comets. It is tempting to believe that it should also be true for all comets that have been through repeated perihelion passages, because more volatile gases would be lost much faster than water. In Chapter 4 the first direct evidence for the presence of H_2O ice in a comet is presented.

Transport of the Dust

The dust in comets has been observed to be very fine, with sizes ranging from about 0.3 μm to about 10 μm for most of the dust although a small amount in the form of larger particles is sometimes detectable (Sekanina, 1974; Brandt, personal communication) and the existence of an occasional very fragile boulder cannot be excluded on the basis of the present evidence. The dust seems to be composed of at least two materials: an absorbing component and a silicate component; these will be discussed in more detail later.

The subliming ices drag away the dust particles embedded in the icy conglomerate. Starting from zero velocity the dust is accelerated radially outward from the nucleus, as a result of free molecular drag interaction between the dust and the expanding gas. Probstein's (1968) model for this interaction describes the dust behavior as a continuous fluid. He concludes that the acceleration of the dust occurs within 20 comet radii; beyond this point the interaction with the gases of the expanding coma is negligible and the behavior of the dust will depend on a parameter B which is the ratio of the force due to radiation pressure (which depends on the optical characteristics of the particle) to the gravitational force. Finson and Probstein (1968a,b) have developed Probstein's fluid dynamics approach to explain quantitatively the isophotes in dusty comets.

The maximum size of a dust particle that would be carried out by the subliming gases, and the possibility of the formation of a mantle of large dust particles, is discussed by Mendis and Brin (1977, 1978), Brin and Mendis (1979), and Brin (1980). Their work indicates that the subliming ices can carry away, at a given distance from the sun, particles much larger than the largest observed in most comets. This suggests that the particle size distribution observed for most comets is not an artifact of the sublimation process.

Once the solids have been ejected from the nucleus they form the dust coma and tail of the comet; at this stage dynamical analysis and photometric studies can de made to determine their characteristics. In this work infrared photometry and spectrophotometry is used to study the solid component of comets.

The infrared is an ideal region of the spectrum in which to study the solid component of comets. Photometry from 1 to 20 μm reveals the both the thermal and reflected parts of a comet's IR spectrum, which gives information on the characteristics of the particles scattering and emitting this radiation. It has only been recently that infrared observations have been available and have contributed to our understanding of comets. The first infrared observations were those of Comet Ikeya-Seki 1965 VII by Becklin and Westphall (1966). Comet Bennett 1970 III was the second one to be observed and in it the 10-μm silicate feature was first detected

(Maas, Ney, and Woolf 1970). Spectrophotometry of this feature was done by Hackwell (1971), and in Comet Kohoutek by Merrill (1974), showing a close resemblance to that seen in emission around supergiant circumstellar shells and in absorption towards the galactic center. Comet Kohoutek was well observed: Gatley et al. (1974), Ney (1974a, b), Rieke and Lee (1974), Rieke et al. (1975), and Zeilik and Wright (1974). The infrared spectra of these comets show a series of common features, namely: 1.) a solar spectrum produced by sunlight scattered by the dust particles; 2.) a thermal continuum hotter than a rapidly rotating black body at the same heliocentric distance; and 3.) two broad emission features centered at 10- and 18-μm. The crossover from scattered radiation to thermal emission depends on the heliocentric distance and it occurs at about 3 μm at 1 AU. Fluctuations in the strength of the 10-μm feature and of the shorter-wavelength thermal continuum on a time scale of days were observed in Kohoutek by Ney (1982) and Rieke and Lee (1974), and in Comet West by Rieke (1977). Rieke also pointed out the disappearance of the 10 μm feature in Kohoutek and West at heliocentric distances greater than about 2 AU. The antitail of Kohoutek did not show the 10-μm feature observed in its coma and tail; this has been attributed to the particles in the antitail being too large (radius > 10 μm) to show the feature (Ney 1982; Sekanina 1974). Comet Bradfield 1974 III showed a silicate feature at 0.5 AU from the sun, but this disappeared at 0.6 AU and the comet suffered an abrupt decrease in brightness indicating a sudden drop in grain production (Ney 1974b). Rieke suggests we may have observed in this comet the exhaustion of the last available dust pocket in a nuclear matrix of less dusty material. Comet Kobayashi-Berger-Milon 1975 IX, with a predominantly gassy tail, showed strong thermal emission without a 10-μm feature, indicating the presence of large or nonsilicate grains (Ney 1982). Comets West and Bradfield 1980t were observed at a variety of scattering angles including forward scattering, their scattering function showed a strong forward enhancement (Ney 1982).

Until recently the only infrared observation of a periodic comet was that of Encke by Ney (1974b). Since then, a set of nearly simultaneous reflected and thermal observations of periodic comets Encke, Chernykh, Kearns-Kwee, Stephan-Oterma, and Tuttle were made by Campins, Rieke and Lebofsky (1982a and Chapter4); A'Hearn et al. (1981) observed Stephan-Oterma and Tuttle, and Hanner, Veeder, and Matson (1981) observed Stephan-Oterma. All the authors just mentioned plus Jewitt et al. (1982) observed Comet Bowell 1980b, a faint and peculiar nonperiodic which showed a coma since its discovery at 7.3 AU.

Most of our information about cometary nuclei comes from studies of the coma. The direct observation of a bare comet nucleus using groundbased optical telescopes is extremely difficult, due to the dust and gas coma present around the nucleus at small heliocentric distances, or due to the faintness of the nucleus when it is not active (possibly the only direct observation of acomet nucleus has been the radar detection of Comet Encke by Kamoun et al. ((1982). Therefore the structure and composition of the nucleus must be inferred based mostly on our knowledge of the gases and solids in the coma.

The objective of this study is to determine the physical characteristics of the solids in comets, in order to allow a comparison between periodic and nonperiodic comets, and between cometary solids, interstellar, and interplanetary dust. This is attained using infrared observations to establish the nature of the coma grains. A total of 7 comets were observed, 5 were periodic and 2 were nonperiodic. The periodic comets were of great interest because infrared observations of this class of objects were almost nonexistent. Both of the nonperiodic comets were also very exciting: Comet West split near perihelion into 4 fragments, and Comet Bowell was unusually bright and active at large heliocentric distances, allowing the detection of a water ice absorption feature in its spectrum.

CHAPTER 2

OBSERVATIONAL TECHNIQUES

All the observations presented were obtained using the infrared system and techniques described by Low (1973) and Low and Rieke (1974). Following is an outline of the process followed to obtain such measurements.

The Photometric System

A set of photometric bands, summarized in Table 1, defines the photometric system. These bands coincide with atmospheric windows and their effective wavelengths, λ_0, are given by the formula:

$$\lambda_0 = \int \lambda\phi(\lambda)d\lambda \Big/ \int \phi(\lambda)d\lambda \tag{3}$$

where (λ) is the total instrumental response function including the filter and atmospheric transmission, mirror reflectivities and detector response. To a first-order approximation, the observed fluxes behave like monochromatic fluxes at a wavelength λ_0. However, because the comets were at much lower temperatures than the standard stars, adjustments had to be made at the thermal wavelengths to correct for the difference in the slopes of thermal curves. The observed fluxes through each band are often given on a magnitude scale with an absolute calibration originally given by Johnson (1965) and improved by Low and Rieke (1974). The absolute calibration is based on the observation of solar type stars with this system. Assuming that the average colors of these stars are the same as the solar colors, then it is possible to calibrate the photometric system through measurements of the absolute solar flux. A selected group of solar type stars chosen from the list given by Hardorp (1982) is presently being observed to improve further the absolute calibration of the system.

Although the photometric bands correspond to atmospheric windows, nevertheless, the atmospheric extinction has to be determined and corrected for. Observations of standard stars at a variety of zenith angles (airmass) are used to determine the extinction curve. For some bands, such as M and especially Q, the extinction is particularly high and variable due to strong water absorption bands in the atmosphere, in these cases, accurate extinction measurements are essential. For other bands, where the extinction is low, average values can be used if accurate measurements for that night are not possible. Some narrow filters are also used in this system; their characteristics are also given in Table 1.

Detectors

Shortward of 5 μm liquid nitrogen- and liquid helium-cooled indium antimonide (InSb) detectors were used; longward of 5 μm a liquid helium-cooled gallium-doped germanium bolometer was used. The detection mechanism of each of these devices is as follows:

TABLE 1.

THE PHOTOMETRIC SYSTEM

Filter	λ_0 (μm)	$\Delta\lambda$ (μm)
J	1.25	0.27
H	1.63	0.35
K	2.22	0.60
L	3.50	1.05
M	5.0	1.0
N	10.6	5.3
Q	21.0	11.0
1.5	1.50	0.1
1.7	1.70	0.1
2.0	2.0	0.1
2.1	2.11	0.1
2.2	2.20	0.1
2.3	2.35	0.1

1) The InSb detectors are photovoltaic, i.e., they absorb photons in a semiconducting substrate containing a p-n junction, creating electron-hole pairs which are separated by the junction causing a potential difference to appear across the junction, which is capable of sustaining a current. In practice these detectors are used as current generators rather than voltage generators, since this permits excess noise to be eliminated.

2) The bolometer is a thermal detector, i.e., radiation is absorbed in a substrate which has a temperature-dependent electrical resistance. The detector is kept at a very low temperature (1.2 K in this case) and as infrared radiation is absorbed and its temperature increases, the drop in its resistance can be measured.

A bolometer is best suited for observations under high back ground conditions ($\lambda > 5$ μm). On the other hand the InSb detectors work best under low background conditions, reaching sensitivities close to the theoretical limit; because of the energy gap between bound and free carriers, InSb detectors cannot detect photons with wavelengths longer than about 5 μm.

Modulation

Infrared photometry at 10 μm, for example, is particularly difficult since the sky and instrument brightness, in this wavelength region, are about one million times that of the source to be measured, and show spatial and temporal variations. Therefore, the rejection of background variations is essential to the performance of any instrument at these wavelengths.

In the simplest possible case, the infrared detector is coupled to a recorder through an amplifier. The telescope is then moved alternately between the sky plus source and the sky and the difference between the two readings is taken. In practice, it is more complicated because this simple method will not cancel the low frequency noise in the detector or slow changes in the telscope and sky background. In this work this problem was solved using telescopes with "chopping" secondary mirrors which make the detector switch between the sky plus source (designated as the positive beam) and the sky, at about 15 Hz. Every few seconds the telescope would "wobble", which causes the sky plus source to be sampled by the negative beam, while the positive one samples the sky. A "lock-in" amplifier keeps track of the chopping giving as output a deflection proportional to the brightness of the source, but with alternately positive and negative signs with each wobble. The minimum measurement consists of one positive observation, one negative and again one positive, the first and third are averaged and the second subtracted to cancel first order drifts in the zero point.

This concludes a very simplified outline of the techniques of infrared photometry. Aperture size, and chopper throw and direction are given with each set of observations presented in this work.

CHAPTER 3

ANALYSIS

In order to interpret properly the photometry, certain assumptions were made, the errors involved were evaluated, and finally theroetical models were produced to compare with the observations.

Assumptions

Albedo

The albedo of the particles can be derived from the relative strength of the thermal and scattered radiation using the expression given by O'Dell (1971):

$$\frac{\gamma}{1 - \gamma} = \frac{S_\lambda}{S_{th}} \frac{F_o}{F_{o\lambda}} \tag{4}$$

where is the albedo, averaged over the region of maximum solar emission, and for the specific scattering angle at which the comet is observed. S_λ is the surface brightness of the comet in reflected light at wavelength λ. S_λ is the thermal surface brightness of the comet, integrated over all wavelengths at which thermal emission occurs. F_0 is the integrated solar flux over all wavelengths, and $F_{0\lambda}$ is the solar flux per unit time, area, and wavelength interval at the same wavelength at which the comet's reflected light was observed.

In theory, the evaluation of the albedo of cometary dust requires observations of the comet's reflected and thermal spectrum over all scattering angles. This is impossible in practice, and often observations at only one or two scattering geometries are obtained. O'Dell did not consider the phase dependence of light scattered by the comet particles. However, Ney and Merrill (1976) and Ney (1982b) have shown that Comets West and Bradfield 1980t had a phase function strongly peaked in the forward direction. Ney (1982b) gives a phase function obtained from observations of 5 comets. This phase function has been used in this work to calculate the average albedo of the comets observed.

There are two other complications in obtaining the appropriate observations to do albedo calculations. One of them is the observation of the complete thermal spectrum of the comet, which is not always possible; however, from observations of a number of bright comets (Ney 1982b) it is known that the shape of the thermal spectrum of the cometary dust resembles that of a blackbody and that the total energy emitted by the dust can be estimated without much uncertainty if an observation is made near the expected peak of the thermal emission. The other complication is the determination of the reflected continuum. The visual spectra of comets show abundant emission lines which can contaminate observations. The paucity of gaseous emissions longward of 1 μm in the spectra of comets make this a very appropriate region in which to study the scattered continuum. To date the only detections of gaseous emissions in this region have been those reported by Potter et al. (1974) in Comet Kohoutek and those observed in Comet West by Johnson, Fink, and Larson (1982).

This spectrum of Comet West covers from 0.9 to 2.5 μm and shows strong CN emission within the J (1.25 μm) band. This emission may contribute a significant fraction of the J-flux in gassy comets which are close to the Sun, in these same comets the K band can include a significant thermally reradiated contribution. So, for these reasons, the H filter has been chosen to define the continuum in all the albedo calculations.

Coma Structure

In order to compare observations made with different apertures, it is necessary to know the radial dependence of the coma brightness. Probstein (1968) argues convincingly that the acceleration of the dust by the expanding gas takes place within 20 nuclear radii of the surface of the nucleus. The number density of particles if the dust expands isotropically at a constant velocity varies as $1/r^2$. If one assumes an optically thin dust coma (which is valid for all comets observed) then the surface brightness of the coma (in reflected or thermal light) should be proportional to the number of scattering particles along the line of sight, which varies as $1/r$ in this case. Now, the total brightness of the comet will be the integral of the surface brightness over the area of the aperture used:

$$B_T = \int \frac{\sigma_o}{r}\, da = \sigma_o \int \frac{2\pi r}{r}\, dr = 2\pi\sigma_o r \Big|_o^r \qquad (5)$$

where $_o$ is the central surface brightness of the coma. Therefore, the brightness of the comet should be proportional to the aperture radius.

This dependence has been confirmed observationally in several comets (Gatley et al. 1974; Rieke and Lee 1974; S. Larson, personal communication), and holds for reflected and thermal light. This relation breaks down because of radiation pressure at large distances from the nucleus ($r \sim 10^5$ km at 1 AU); however, in all the observations presented in this work, the apertures used were well within the expected breakdown radius.

Errors

The standard errors for the magnitudes given in this work reflect only the precision of a particular measurement, which is calculated as the standard deviation of the mean of a series of observations. In a photometric night, the main source of error for observations where the thermal background is high, are the fluctuations in the background. On the other hand, for observations at J, H and K, the main source of error may be the fluctuations in the detector noise, since at these wavelengths one is usually detector limited.

As in any photometry the precision of the measurements is further degraded by rapidly changing atmospheric conditions, inaccurate tracking, and incorrect alignment of the infrared and visual axis. These errors are not necessarily included in the standard errors given for each observation; however, they can be minimized by careful observing procedures. The uncertainty of the absolute calibration of the infrared photometric system is between 5 to 10%, and will affect the absolute value of the fluxes obtained.

Theoretical Models

The observations obtained can be used to compute directly certain characteristics of the cometary solids such as temperature or albedo. They can also be used to constrain models of the grains when some of the characteristics of interest are not uniquely derivable from the observations alone. Two different types of modeling were done: scattering of sunlight and thermal emission.

Scattering

In order to study the behavior of the 1.5, 2 and 3 μm absorption bands of frost grains containing different amounts of dust and to compare the results with the observations of Comet Bowell, Mie scattering models were generated. The models use the formulae for light scattering by homogeneous spheres of arbitrary radius worked out by Mie and Debye, and given by Van de Hulst (1957). The scattering properties of a sphere of radius "a" for light of wavelength may be determined in terms of parameters:

$$x = 2\pi a/\lambda \tag{6}$$

$$m = n' - in'' \tag{7}$$

where n' and n" are respectively the refractive and absorptive indices.

In Chapter 4 the results of these models are discussed and compared with the observations.

Thermal Emission

The emission of thermal radiation by the cometary grains depends not only on their heliocentric distance but also on their size distribution and composition (which determines their optical constants). Therefore the behavior of the thermal continuum of comets can be modeled to determine the size distribution and constrain the composition of the particles. The steps are as follows:

1) Guess a size distribution characterized by certain parameters <a> and <b>. (In this work the one used has been derived from dynamical considerations and is given in Chapter 4.)

2) Guess a composition and, using the optical constants of the material guessed, determine the temperature of the grains as a function of size and heliocentric distance using the formula from Hanner (1980) equating the total energies absorbed and emitted:

$$\pi a^2\left(\frac{r_o}{r}\right)^2\int Q_{abs}S_\lambda d\lambda = 4\pi a^2\int \pi B_\lambda(T)Q_{abs}d\lambda \qquad (8)$$

where r is the heliocentric distance and r_0 is 1 AU, S_λ is the solar flux at each wavelength, Q_{abs} is the absorption efficiency factor computed from Mie theory; $B_\lambda(T)$ is the Planck function at a temperature T, and a is the particle radius.

3) Predict an emission spectrum and compare it with the observations.

4) If the fit is not good, change <a>, <b> and/or the composition of the particles and go back to step 2.

5) If the fit is good, the optical depth of the coma can be determined knowing the shape and absolute value of the thermal emission (for an optically thin coma).

CHAPTER 4

NONPERIODIC COMETS

In Chapter 1 the previous infrared observations made of bright comets are summarized. In this Chapter I describe the nature of the cometary grains as deduced from these observations. Then I discuss new observations of two extreme comets, Bowell (1980b) and West (1974n) which expand on the picture developed from previous measurements.

Nature of the Cometary Dust

Infrared observations of bright comets have yielded the following general picture of cometary dust: hot absorbing grains, which produce the thermal continuum, with a silicate component (either as separate grains or embedded in the absorbing matrix), which accounts for the 10- and 18-μm emission features. These grains have a size distribution ranging from about 0.3 μm (constrained by the absence of Rayleigh scattering) to about 10 μm (constrained by the presence of the 10-μm silicate emission feature).

Using the method described at the end of Chapter 3, Campins and Hanner (1982) found that magnetite grains (or grains of a magnetite-like absorbing material) with a size distribution peaking at a small range around 1 μm, fit the thermal continuum at 3.5 and 4.8 μm of all comets for which data are available (see Figure 1). The size distribution used is that derived for Comet Bennett 1970II by

Sekanina and Miller (1973), modified for large particles to agree with the analysis of comet antitails by Sekanina and Schuster (1978a,b), and has the following form:

$$\begin{aligned} n(a) &= 0, && 2a\rho < 0.9\times10^{-4} \\ n(a) &= 0.69(2a\rho - 0.9\times10x^{-4})/(2a\rho)^5, && 0.9\times10^{-4} \leq 2a\rho \leq 2.6\times10^{-4} \qquad (9) \\ n(a) &= 0.08656(2a\rho)^{-4.2}, && 2a\rho > 2.6\times10^{-4} \end{aligned}$$

where a = grain radius; and in the case of Comet Bennett, ρ is the grain density in grams/cm^3. For the other comets, however, no dynamical analysis exists and the grain density is not restricted from observations, and ρ becomes a dimensionless parameter to describe the shift in mean particle size (proportional to $1/\rho$).

In Figure 1 all the observations fall between the curves for $\rho = 1.0$ and $\rho = 2.0$; the extensive observations of Comet Kohoutek (Ney 1974b) are matched fairly well by a model with $\rho = 1.33$. The single point for P/Encke falls very close to the same curve. The mean particle size does not change for abrupt changes in brightness (Comet Bennett at 0.64 versus 0.94 AU), loss of the silicate feature (Comet Bradfield 1974III at 0.67 AU) or complete absence of a silicate feature (Comet Kobayashi-Berger-Milon 1975IX).

Silicates, which are also present in cometary dust, do not absorb very efficiently in the visual and are not by themselves good candidates to produce the thermal continuum. Olivine, an iron magnesium silicate, shown by Hanner (1980) to give a reasonable fit to

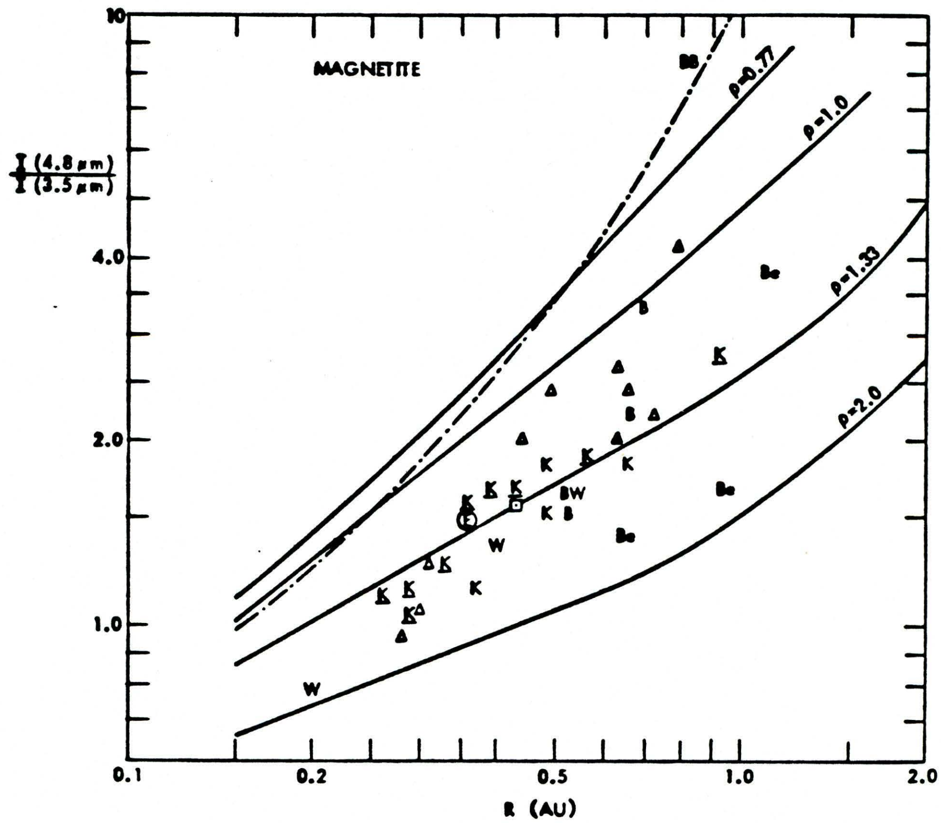

Figure 1. Flux ratio I(4.8 μm)/I(3.5 μm) vs. heliocentric distance for five comets. (From Campins and Hanner 1982)

The plot shows the comparison of observations with models for size distributions of magnetite grains, varying size parameter p in Eq. (8). The dash-dot curve represents the theoretical blackbody (BB). K and K̲: Comet Kohoutek 1973 XII pre- and post-perihelion (Ney 1974); B: Bradfield 1974 III (Ney 1974a); Be: Bennett 1970 II (Ney 1974a); W: West 1976 VI (Ney and Merrill 1976); ⊡: Bradfield 1980t (Ney 1982); Δ: Kobayashi-Berger-Milon 1975 IX, average of 5 observations near 0.43 AU (Ney 1982); E: P/Encke (Campins et al 1981b).

the 10- and 18-μm silicate features observed in Kohoutek by Ney (1974b), has been adopted to model the silicate component. In order to make the olivine grains hot, they have to be made dirty. (Brownlee ((1978) frequently found, in interplanetary dust, silicate particles embedded in chondritic material or silicate grains with dark material clinging to their surface). This is attained by increasing their imaginary index of refraction n".

Figure 2 shows a similar plot for a model of amorphous olivine with imaginary index of refraction n" = 0.001 (dotted curve), n" = 0.01 (solid curve), and n" = 0.04 (dashed curve). When n" = 0.001, the small silicate grains are much colder than a blackbody (Figure 3). The thermal emission at λ = 8 μm arises mainly from the larger grains (50% from $a \geq 100$ μm, if $n(a) \propto a^{-4.2}$). Therefore, changing the mean size of the smaller grains does not alter the 4.8 μm/3.5 μm brightness ratio. Thus, thermal emission would not, in fact be oberved, if n(a) follows Equation (9); the scattering of sunlight by the small grains would be stronger than the thermal emission (by a factor of 75 at λ = 3.5 μm at 0.75 AU). For n" = 0.01 or 0.04, the small grains being hotter, make a larger contribution and a small effect of cutoff size is present, as illustrated for n" = 0.01 (ρ = 1 and ρ = 2).

The most significant aspect of Figure 2 is that the slopes of these curves for olivine differ markedly from the slope of the observations, particularly for Comet Kohoutek, which has the most extensive coverage in heliocentric distance. The only comets for which the slope might be considered comparable to that of the olivine with n" =

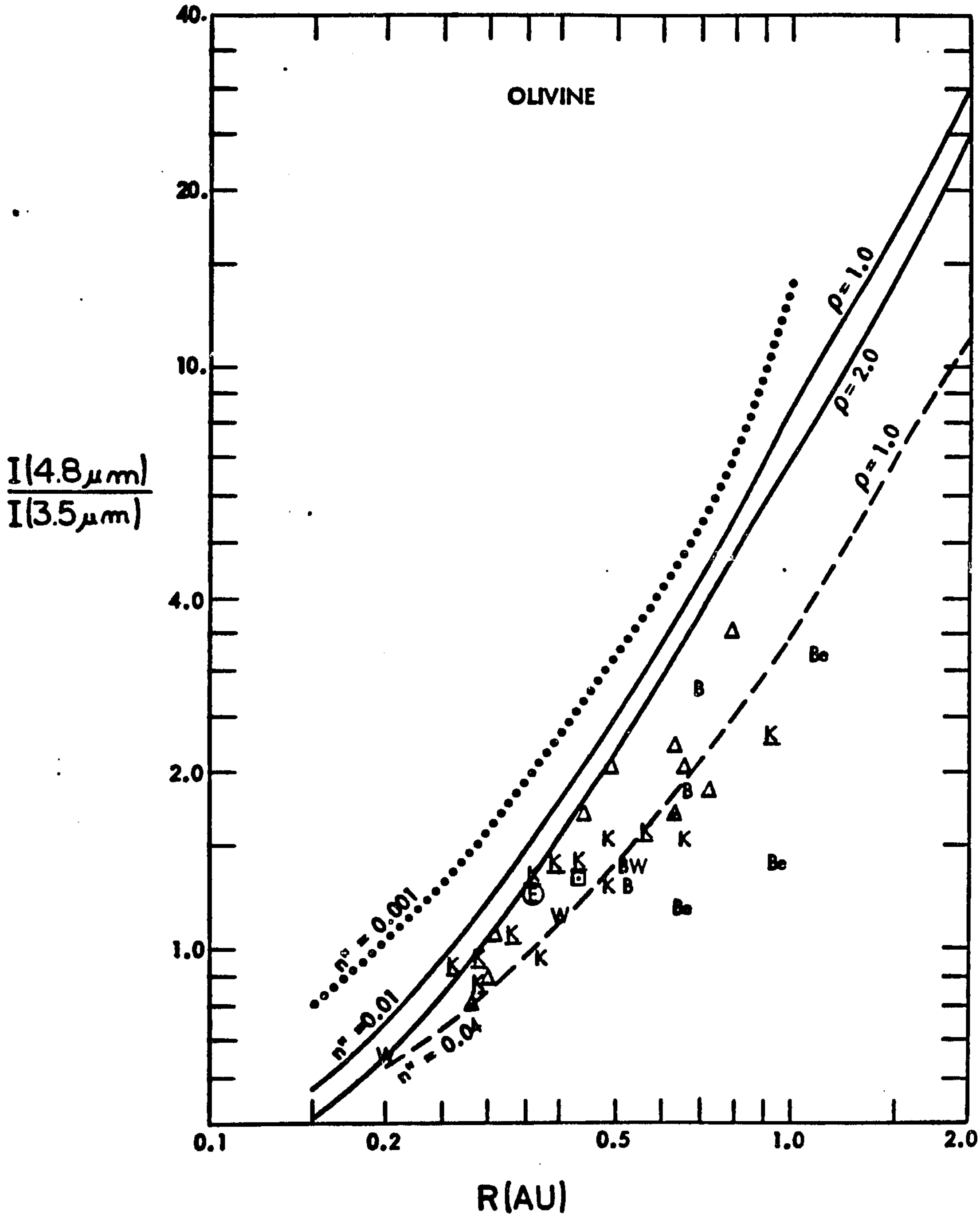

Figure 2. Flux ratio I(4.8 μm)/I(3.5 μm) for size distribution of silicate grains, compared with the same observations as those in Figure 1, with imaginary index of refraction n" and size parameter ρ as indicated. The curve n" = 0.001 is independent of ρ.

0.04 are the cases in which the silicate feature disappeared. Furthermore, Hanner (1980) showed that a close fit at 3.5 and 4.8 μm by dirty olivine would produce too strong a feature at 10 μm.

This leads to the conclusion that particles with a size distribution peaking in the range shown in Figure 1 and composed mostly of a highly absorbing material (magnetite, graphite, or others) are responsible for the thermal continuum of all comets for which data are available. This is particularly significant because the seven comets range from "new" (Kohoutek) to very evolved (P/Encke).

Comet West

This comet was observed a total of 9 nights by G. H. Rieke using the 154-cm and the 229-cm telescopes. A 6 arcsec aperture was used and the measurements were made with respect to beams 9 arcsec east and west of the nucleus or nuclei. The results are summarized in Table 4 and Figures 4, 6, and 7. Following is a discussion of the properties of the dust in this comet based on these observations. First a comparison with Comet Kohoutek is made. Then the cometary silicate features in both comets are compared to those found in the interstellar medium and in carbonaceous meteorites; next, after the nucleus of Comet West split, the fluctuations in the silicate spectra of the different nuclei and their implication on the structure of the nucleus are examined; and finally the disappearance of the silicate feature at large heliocentric distance is discussed.

TABLE 2.

PHOTOMETRY OF COMET WEST.

Date (1976)	Nucleus	r (AU)	J	H	K	L	M	8.4	8.8	10.4	N	11.6	12.6	16.4	17.9	19.0	Q	Q+
3-8		0.45	----	----	3.27	0.29				-4.64	----	-4.59	4.40	-5.85	-5.60	-5.70	-5.79	-5.63
3-31	A	1.00	----	----	----	----	----	1.27	----	0.83	0.32	0.65	0.94	----	----	----	----	----
	D		----	----	----	----	----	1.43	1.36	0.35	0.66	0.91	1.26	----	----	----	----	----
	B		----	----	----	----	----	2.41	2.02	1.37	----	1.12	1.30	----	----	----	----	----
4-1	A	1.03	----	----	9.09±0.18	8.33±0.22	5.80±0.13	2.43±0.08	1.50	1.10	----	2.06	----	----	----	----	----	----
	D		----	----	9.33±0.16	----	6.24±0.07	----	1.65	0.41	----	2.28	----	----	----	----	----	-1.33
	B		----	----	10.30±0.33	----	6.48±0.18	3.54±0.14	2.23	----	----	----	----	----	----	----	----	0.97±0.33
4-3	A	1.06	----	----	9.32	7.40	5.45	1.37	----	0.66	----	----	-0.13	----	----	----	----	----
	D		----	----	9.24	7.77	5.91	1.31	----	0.37	----	----	-0.30	----	----	----	----	----
4-4	A	1.07	----	----	----	----	----	----	1.67	0.70	1.07	0.53	0.48	----	----	----	----	----
	D		----	----	----	----	----	----	1.75	0.92	----	0.50	0.60	----	----	----	----	----
4-19	A	1.39	----	----	----	----	----	3.15	----	1.82	----	----	1.45	----	----	----	----	-0.27
4-28	A	1.54	----	----	----	----	----	3.34	----	1.93	----	----	1.30	----	----	----	----	----
	D		----	----	----	----	----	3.88	----	2.98	----	----	2.25	----	----	----	----	----
5-1	A	1.62	----	----	----	----	----	3.23	2.86	2.14	----	1.84	1.64	----	----	----	----	0.18
5-27	A	2.06	----	----	----	----	----	4.40±0.20	----	3.27±0.12	----	----	2.55±0.20	----	----	----	----	----
5-29	A	2.09	12.30±0.03	11.94±0.04	1.75±0.05	----	----	----	----	----	----	----	----	----	----	----	----	----

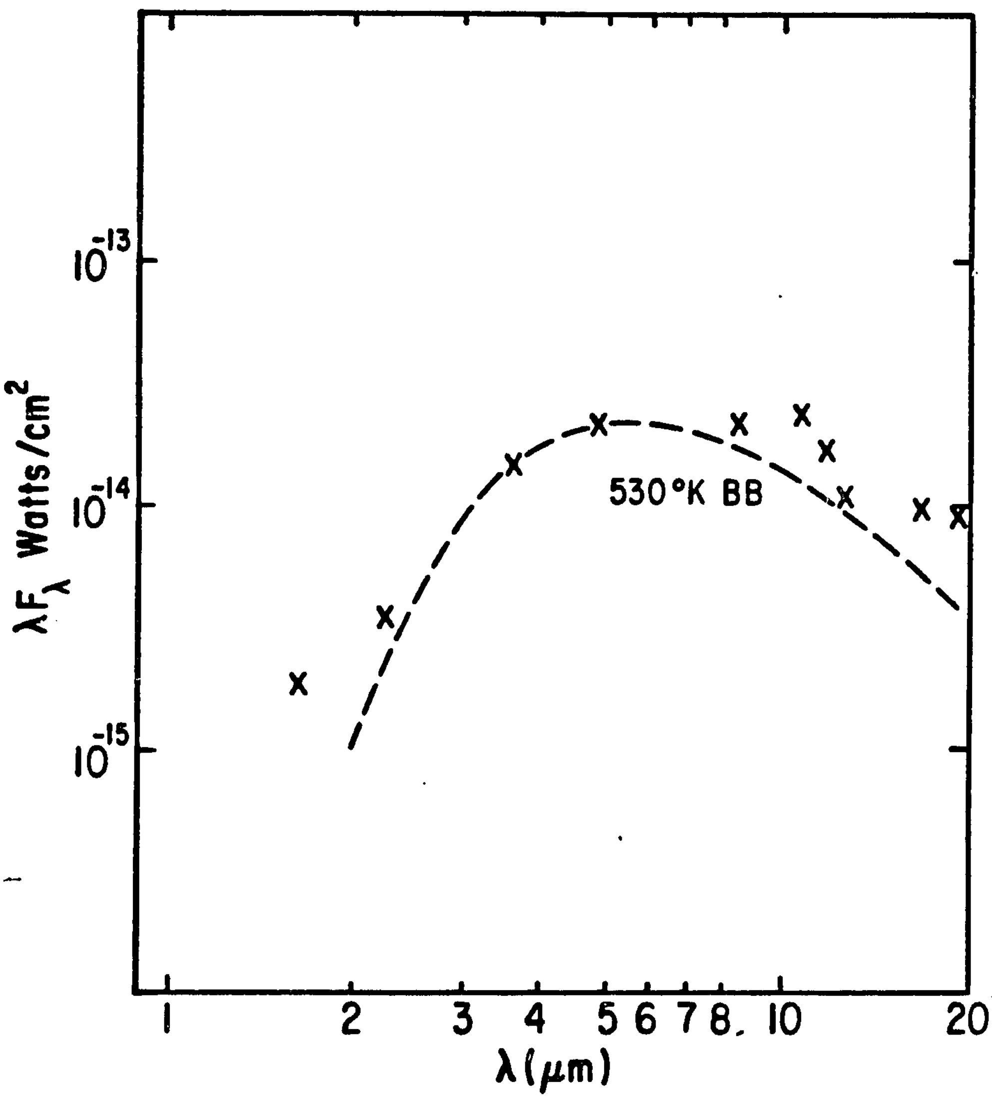

Figure 3. Observations of Comet Kohoutek on December 19.7 1973 (Rieke and Lee 1974). The dotted line is a 530° K blackbody curve which has been fit to the L and M points.

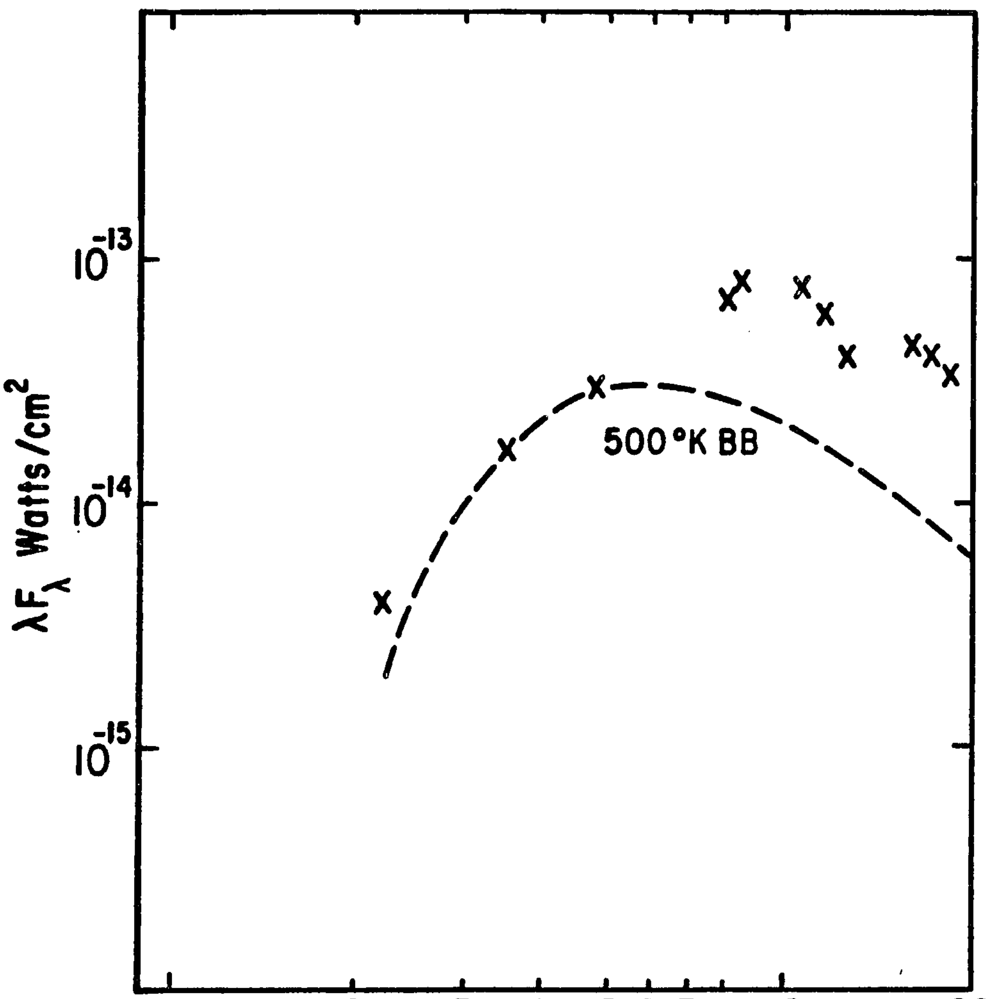

Figure 4. Observations of Comet West on March 8, 1976.

Comet West is an "evolved" ($10^{-3} < 1/a < 10^{-2}$ AU), non-periodic (Period > 200 yrs) dusty comet, Kohoutek, on the other hand, is considered a "new" comet ($1/a < 10^{-4}$ AU) with an intermediate dust to gas ratio (Donn 1977). These two comets are of special interest because they were bright enough to allow a detailed study of their emission spectrum and observations were obtained over a wide range of heliocentric distances. As in all other comets observed in the infrared there is no evidence for Rayleigh scattering in the J, H, K colors of these comets, this indicates that small particles (radius < 0.3 μm) are not very abundant in their comae. The presence of the 10-μm silicate emission indicates grains with a < 10 μm. The size range of the dust in both comets is restricted to these limits, however, Comet West exhibits a higher temperature excess than Kohoutek at similar heliocentric distances indicating smaller grains. Smaller grains can produce a stronger silicate signature (Hanner 1980) but as Rieke (1977) points out, a correlation between temperature excess and strength of the 10-μm feature was not apparent for comet Kohoutek or between Kohoutek, Bennett and Bradfield. Therefore, variation in the composition of the dust probably accounts for some of the difference in the strength of the emission features in comets Kohoutek and West (Figures 3 and 4), i.e. the dust in comet West had a larger ratio of silicates to absorbing material. This is in agreement with the albedo of the dust in comet West being larger than that of Kohoutek (Ney 1982) since pure silicates have a very high albedo at optical wavelengths. As we can see the dusty components in these comets differ

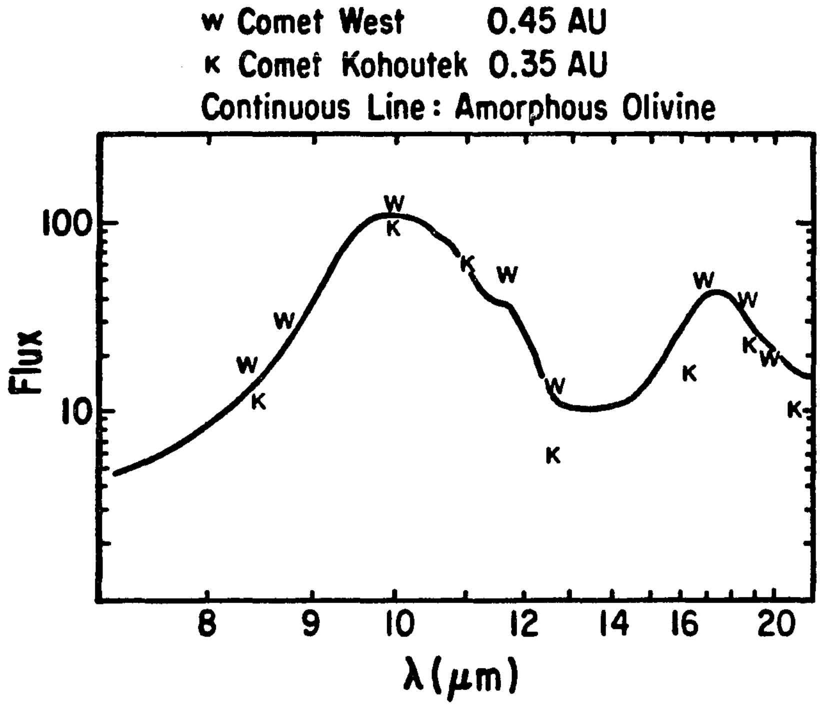

Figure 5. The 10- and 18-μm feature of comets Kohoutek and West are plotted along with the same features in amorphous olivine (from Kratsmer and Huffmann 1979). The cometary observations were ratioed to the blackbody continuum and normalized to 100 in arbitrary flux units.

appreciably in particle size distribution and probably in composition, but only within a small range considering their vastly different dust to gas ratios (Ney 1982).

The silicate emission features observed in most comets are also present in West. There have been two spectrophotometric scans of the 10 μm feature of comets Bennett and Kohoutek done by Hackwell (1971) and by Merrill (1974), respectively; however, the only information on the spectral structure of the 18-μm band comes from filter photometry of comets Kohoutek (Rieke and Lee 1974) and West (this work). In Figures 3 and 4 one can see these emission features on top of a blackbody continuum fitted to the L and M points. In Figure 5 the features have been plotted after being ratioed to the continuum and normalized to 100 at 9.8 μm so they can be compared with the absorption bands from amorphous olivine in the same figure (from Kratschmer and Huffman 1979). As Kratschmer and Huffman have pointed out, amorphous olivine gives the best fit to the interstellar features in absorption and emission. Detailed comparison of the strength and shape of the interstellar 18-μm feature is difficult because of complications with separating the underlying continuum and in treating radiation transfer effects; however, there is good agreement in the position of the 18-μm peak. In the case of cometary comae and of laboratory samples these problems do not arise because they are optiλλcally thin cases in which the illuminating source is well known.

Amorphous olivine is therefore considered for the purpose of this study to be the best representative of the interstellar silicates.

Fraundorf et al. (1982) have measured the infrared spectrum of two types of Brownlee particles, which are interplanetary particles collected in the upper atmosphere, and at least some of which are believed to have a cometary origin. One of the particles showed an infrared spectrum which closely matched the CM meteorite Murchison, showing water of hydration features near 3 and 6 μm, and 10 and 22 μm features attributed to hydrated silicates. This particle seems to be of meteoritic origin. The other sample observed was composed of pieces of three similar particles. This second sample showed structure in its 10 μm feature which is more typical of crystalline pyroxene that either amorphous or crystalline olivine. If this second sample is of cometary origin, then the difference in the 10 μm features has to be explained somehow, by the heating or recrystallization of the particle or some other process. However, only one sample has been measured and there is no way to determine its true origin. Furthermore, neither laboratory nor astronomical measurements are good enough yet to provide a crucial test.

Hanner (1980) successfully fit a size distribution of amorphous olivine to the 10 μm spectrophotometry of Kohoutek. The agreement of the Kohoutek spectrophotometry with the olivine and with the interstellar silicates (Merrill 1974) is much better than with the carbonaceous meteorites which have a narrower 10-μm band (Friedmann, Gurtler, and Dorschner 1979). The filter photometry of the 10- and

18-μm features of the comets is also in better agreement with the olivine than with the meteorites which show no feature at 18 μm but rather a feature near 22 μm and a weaker one at 16 μm (Zaikowski and Knacke 1975). This indicates that cometary dust is more closely related to interstellar dust than to carbonaceous chondritic material.

The nucleus of comet West split near the time of perihelion passage into four discrete fragments. On March 8 (Figure 4) although the comet had already split all fragments were still within the aperture used, but on March 31, and April 1, 3, 4, and 28 (Figures 6-10), several of the nuclei were observed separately.

In examining closely Figures 6 and 7 one notices that the shape of the 10 μm feature of each nucleus is the same for both days (Except nucleus 3 for which there were not enough observations on April 1) but varies considerably from one nucleus to another. Nuclei 2 and 3 have emission peaks at 10.4 μm. Nucleus 1, on the other hand had a flatter feature of about the same strength as that of nucleus 2; also note that the strength of the feature on April 1 with respect to the continuum is greater than that on March 8. Further variations between nuclei 1 and 2 occur on April 3 and 4; on April 3 nucleus 2 is still brighter at 10.4 μm than nucleus 1, but the difference is only a slight one;on April 4 nucleus 1 is brighter than nucleus 2 at 8.4, 10.4 and 12.6 μm and about the same at 11.6 μm. On April 28 nucleus 1 is considerably brighter than 2 at all wavelengths.

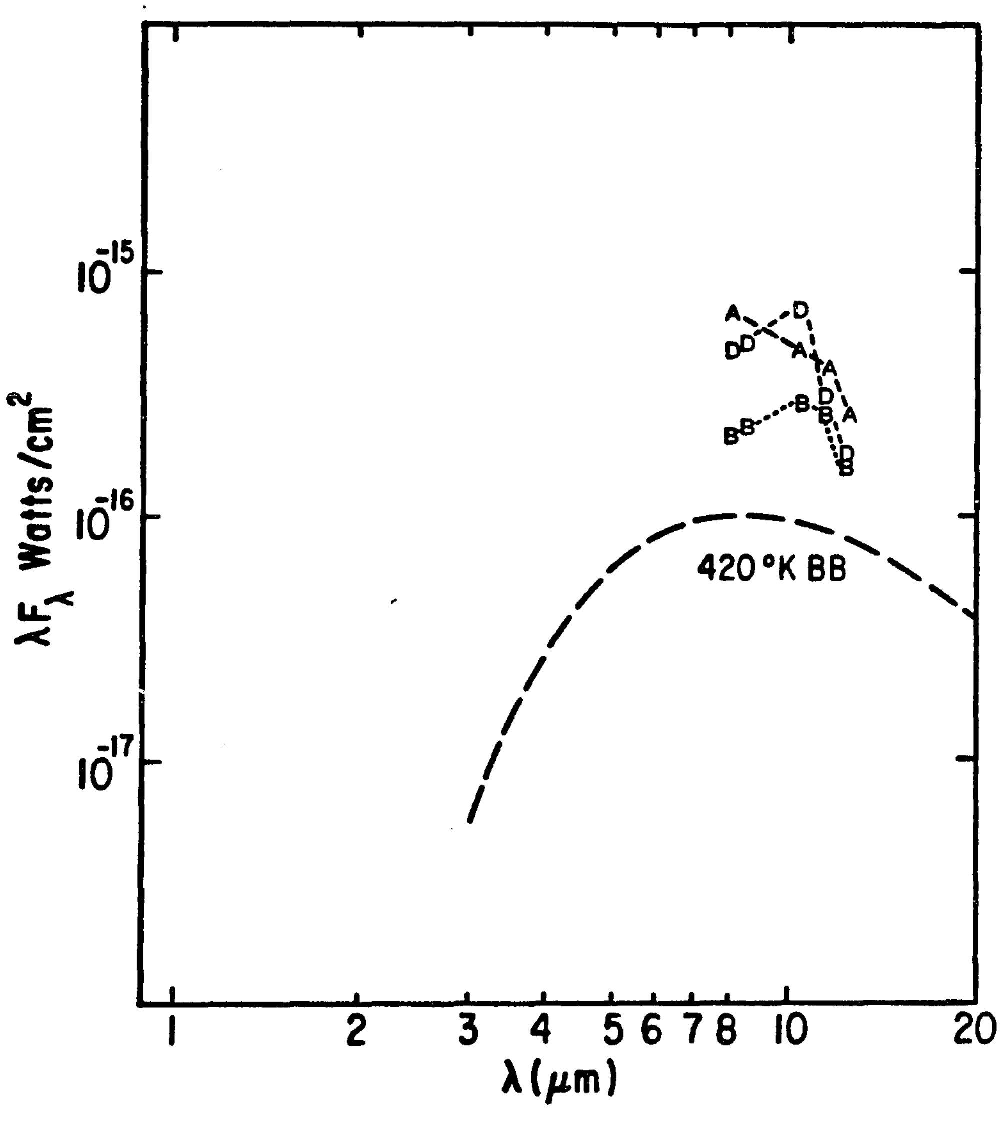

Figure 6. The observations of nuclei A, B, and D of Comet West on March 31, 1976.

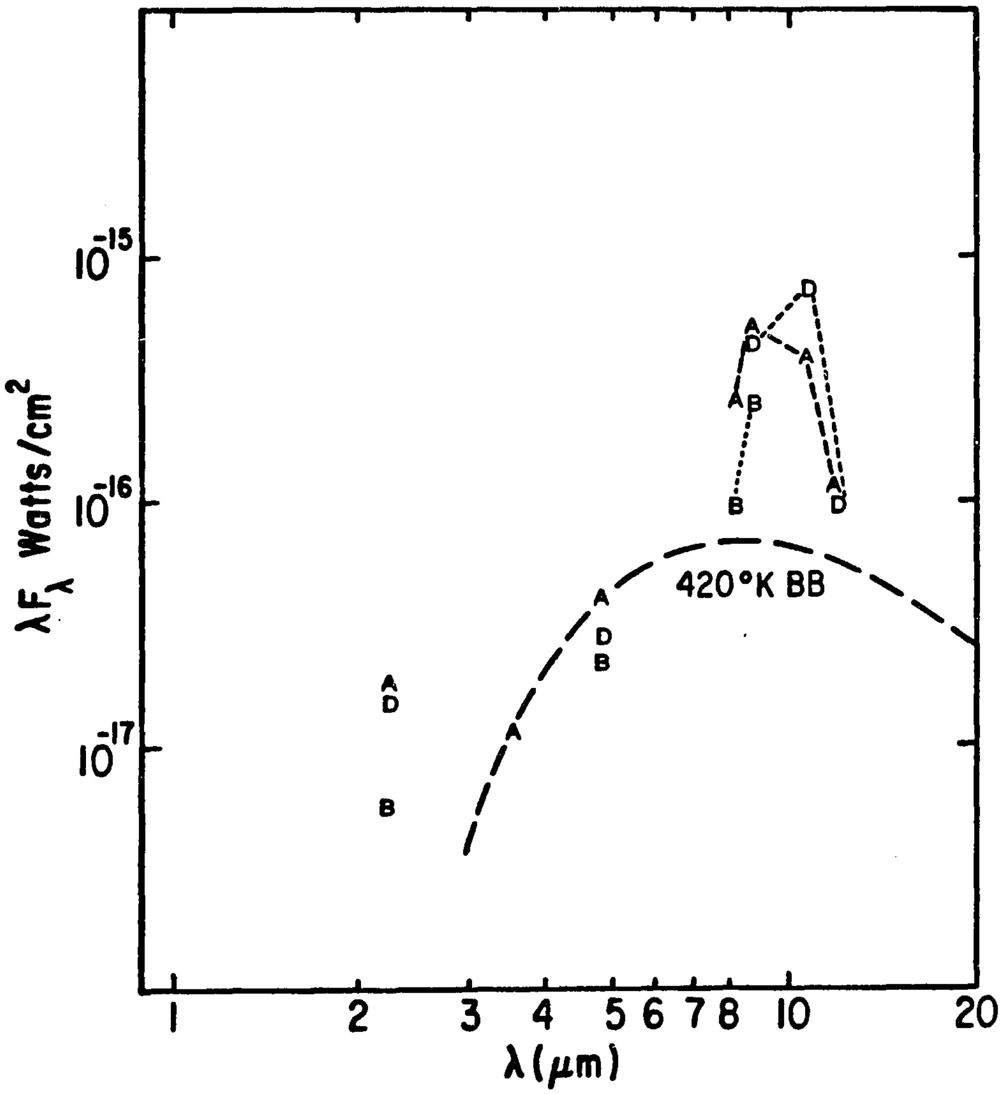

Figure 7. The observations of nuclei A, B, and D of Comet West on April 1, 1976.

The variations in band shape can be attributed to differences in the particle size distribution since the shape of the bands seem to depend on the size of the emitting particles (Hanner 1980). Variations in dust production rate and particle size distribution are not only expected in splitting comets but were observed in West by Sekanina (1976) and by Ney and Merrill (1976). The observations of Comet West reported above are interpreted as follows: on March 31 and April 1 nuclei 2 and 3 were emitting smaller particles than nucleus 1. The size distribution of the dust in nuclei 1 and 2 changed between April 1 and 3, and continued to change on April 4, with nucleus 2 emitting less dust as time progresses, this in agreement with Sekanina (1976) who noted that nucleus 2 was a smaller nucleus which probably had a large proportion of its surface as freshly exposed material producing a large initial activity but also a faster fading. The greater strength of the 10-μm band on April 1 as compared to March 8 may be due to a larger abundance of silicates in the dust emitted on April 1. The expansion velocity of the dust in the coma at this heliocentic distance ($\sim$ 1 AU) is on the order of 1 km/sec (Delsemme 1982), which does not violate the lower limit for the velocity of the dust obtained from temporal variations in the spectra of the nuclear fragments.

In Chapter 1 the evidence in favor of the undifferentiated nature of cometary nuclei is discussed; however, the existence of small scale differentiation resulting from one or more processes (uneven erosion, formation of an outgassed mantle of large dust particles, or even inhomogeneous accretion) can give rise to observable phenomena. An example of this is the behavior of Comet West as it split. According to Delsemme (1982) the behavior of the nongravitational acceleration (due to the jet effect of the subliming ices, Sekanina (1977)) indicates the same sublimation pattern of each fragment after separation, supporting the large scale homogeneity of the nucleus. On the other hand the observations presented here indicate differences in the dust ejected from the different nuclei, and also variations with time in each individual nucleus.

Comet West is the first case of a splitting comet in which the fragments were observed to have differences in their dusty components. These differences are probably due primarily to size distribution, but some compositional variations are also possible. Sekanina (1982) favors a model of splitting comets in which secondary nuclei have a tendency to "peel off" rather than break up. According to this model the secondary nuclei are fragments from near the surface of the main nucleus, where small scale differentiation is most likely to occur.

Fragments of spit comets, including those of Comet West have shown brightness fluctuations. These fluctuations reached amplitudes of up to 3.3 magnitudes and although they were by no means periodic, the fragments' brightnesses were observed to fluctuate faster when closer to the sun. The brightness variations of the secondary nuclei in West are also explained by Sekanina's model. Because of the apparent dependence of the length of intervals between brightness peaks on heliocentric distance, these variations cannot be explained by rotation. On the other hand, a strongly nonspherical, subkilometer-sized fragment could be forced by the torque from asymmetric outgassing to tumble at a high precession rate, fully exposing the fresh surface or hiding it for a while. The pattern of light variations has no strict periodicity and no stable amplitude apparently because of the continuously changing factors that determine the precession rate; however, heliocentric distance is one of these factors.

The 10-μm feature in Comet Kohoutek was shown to have disappeared at about 1.7 AU from the sun (Rieke and Lee 1974). Comet West has shown a similar behavior with the prominent feature observed at small heliocentric distances becoming only marginally detectable at 1.6 AU and completly absent at 2 AU. As pointed out by Rieke (1977) the disappearance of the silicate feature near 2 AU correlates well with the expected stability of clathrate hydrates at this distance. Furthermore the albedo of the grains did not change significantly at this distance and it agrees well with that determined by Ney and Merrill (1976) from earlier observations. This suggests that the water ice may act as a glue which holds the grains in large clumps until they are well removed from the nucleus (Rieke 1977). A model of icy grains in comets at large heliocentric distances (which will be described in detail in the next section) has been developed based on this proposition and on observations of Comet Bowell (1980b).

Comet Bowell

Although the presence of frozen volatiles as the major constituent of cometary nuclei is the basis for the icy conglomerate model. The direct detection of these ices has proven to be difficult: bright comets are generally so close to the sun that icy grains or icy mantles on dust grains are too short lived to make an appreciable contribution to the coma brigtness (Hanner 1981; Sekanina 1975), while comets that are far enough from the sun for ices to survive (heliocentric distance > 2 AU) are usually too faint to be observed adequately.

Observations of the reflected light from comets in the 1 to 5 um region of the spectrum are very diagnostic of the presence of ices. A number of attempts have been made to detect absorption bands in this region (Oishi et al. 1978; A'Hearn, Dwek, and Tokunaga 1981; Jewitt et al 1982).

Comet Bowell offered a better opportunity to search for the spectral signatures of the different species of frost or ice believed to be present in cometary nuclei. It was bright enough to be observable in detail at large heliocentric distances where frozen volatiles such as H_2O are stable in the coma. Furthermore, the fact that this comet is believed to be coming in from the Oort cloud for the first time makes it likely to have a relatively large proportion of frozen volatiles. In this section are the results of two separate observing programs on this comet: the first one executed during 1981 yielded models of the grains constraining their volatile content, the second one in 1982 provided the first direct evidence for the presence of H_2O ice in a comet.

First Program

The comet was observed a total of 4 nights using the University of Arizona 154-cm, 229-cm and Multiple Mirror Telescopes. The observations are summarized in Figures 8, 9 and 10 and in Tables 3 and 4. The apertures used are given in Table 4. The measurements were made with respect to beams 14 arcsec east and west of the nucleus from the 154-cm telescope, and 10 arcsec east and west from the 229-cm telescope, and 10 arcsec above and below in elevation from the MMT.

Figure 8 is a plot of the observed reflectance of the comet in the different bandpasses. These values were obtained by taking the ratio of the absolute flux from the comet to the absolute solar flux given by Labs and Neckel (1970). The absolute flux from the comet at each wavelength was obtained using Bootes, a solar type star (G0 IV), as a standard. Table 3 gives the magnitudes at the same bandpasses as Figure 8.

Figure 9 is the reflectance obtained using the MMT's Circularly Variable Filter (CVF) from 1.94 to 2.34 μm, with a $\Delta\lambda/\lambda$ of 0.01. In this case the reflectance was obtained by ratioing the comet's spectrum to that of β Virgo, another solar type star (F9V).

From Figure 8 we can see that the spectrum of Comet Bowell is redder than the solar spectrum with a J-K of +0.58 (according to Johnson (1965), the solar J-K = +0.32). The J, H and K magnitudes are

TABLE 3.

1.25 TO 3.45 μm MAGNITUDES

λ (μm)	Magnitude	Reflectance
(J) 1.25	13.28 ± 0.03	0.870
1.50	12.83 ± 0.06	0.941
(H) 1.63	12.81 ± 0.02	0.932
1.70	12.75 ± 0.05	0.978
2.00	12.75 ± 0.05	0.962
2.11	12.70 ± 0.05	1.005
2.20	12.66 ± 0.05	1.043
(K) 2.22	12.70 ± 0.02	1.000
2.35	12.60 ± 0.06	1.072
3.25	>11.56 (3σ)	
(L) 3.45	12.90 ± 0.30	1.240

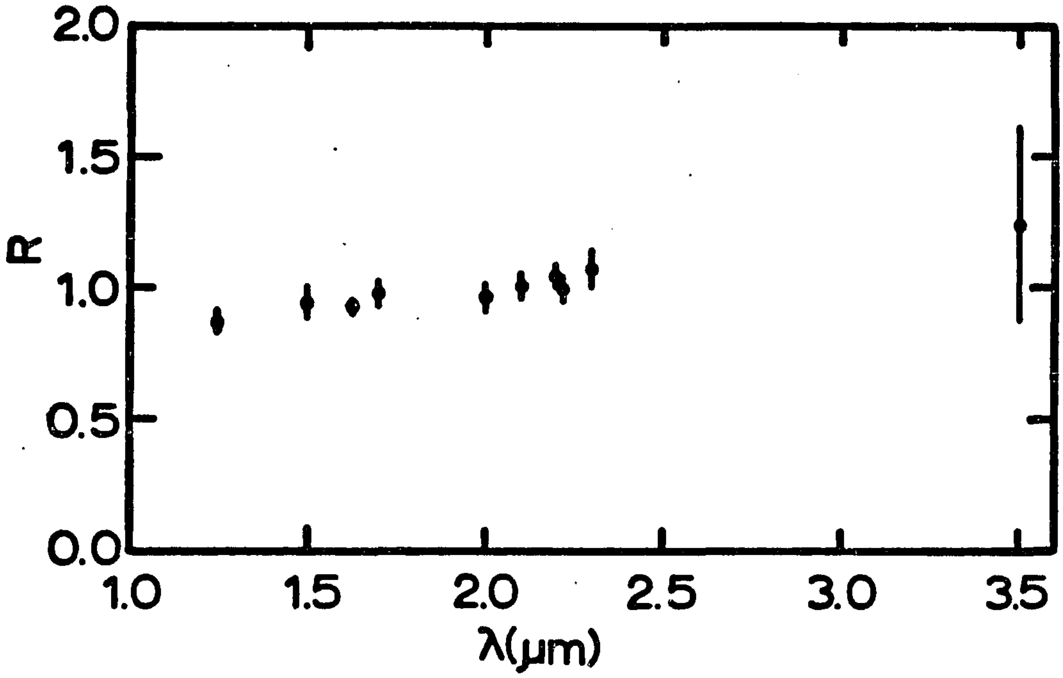

Figure 8. The reflectance of Comet Bowell from 1.25 to 3.5 μm in 1981.

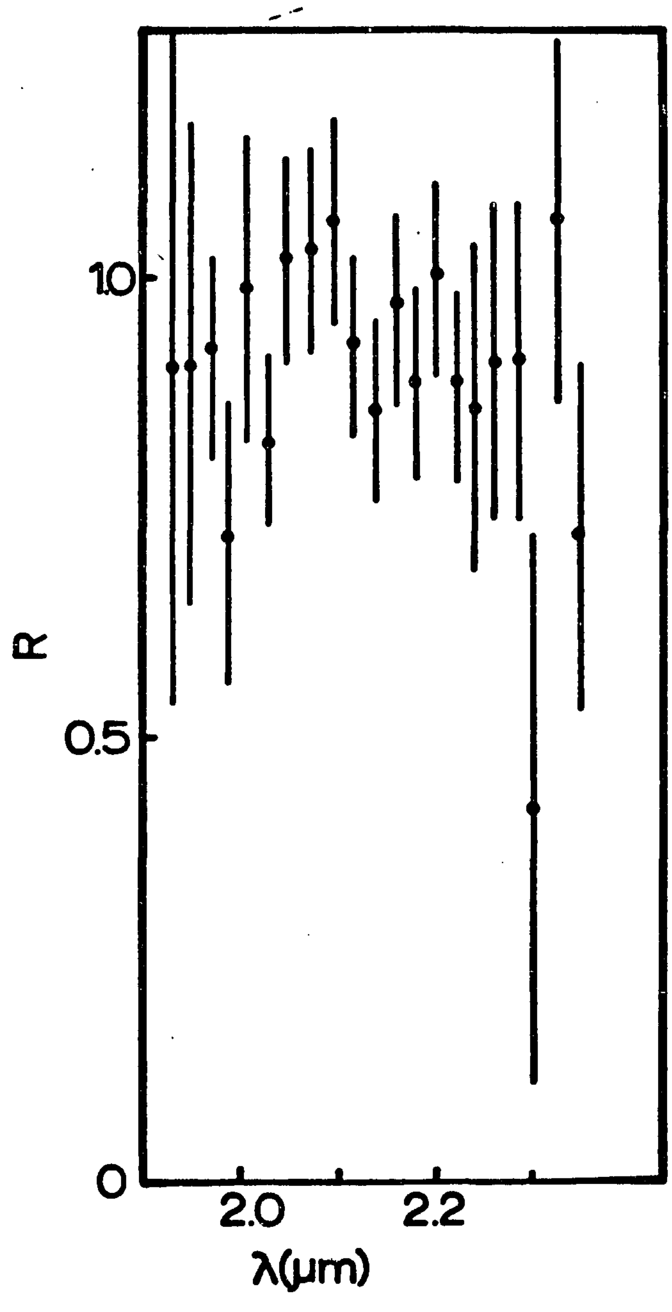

Figure 9. The CVF spectrum of Comet Bowell in 1981.

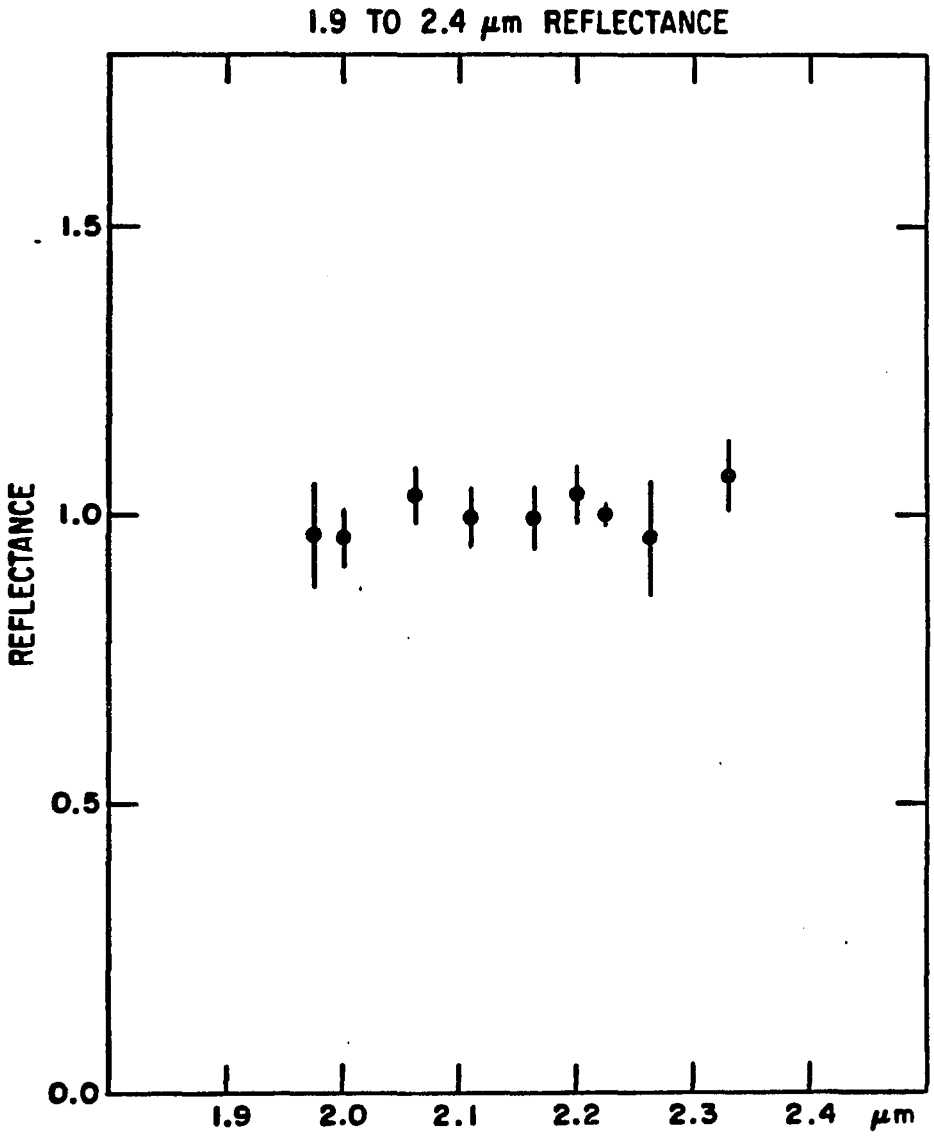

Figure 10. The 1.9 to 2.4 μm reflectance of Comet Bowell in 1981.

in agreement with those of A'Hearn et al. (1981), and Veeder and Hanner (1981). There is no evidence for absorption features in either spectrum.

In Figure 10 we have combined the CVF data into four points at 1.97, 2.08, 2.18, and 2.27 μm, which have been plotted along with the filters from 2.0 to 2.35 μm (from Figure 8). Since the CVF scan and the filters sample the same total flux their averages were set equal and then normalized to 1 at K (2.22 μ). This spectrum, which is fully sampled, has the same spectral resolution as that obtained by Jewitt et al. (1982). Within the claimed errors our spectrum is consistent with theirs, however, ours does not show the marginally detected feature at 2.2 μm. The presence of this feature in Comet Bowell, therefore, remains unconfirmed.

Table 4 gives the K magnitudes, heliocentic and geocentric distances, and scattering angles of the comet on the different dates of observation; also given are the K magnitudes reduced to a single aperture size of 11.5 arcsec. A brightness of the coma proportional to the aperture diameter was assumed when making the K magnitude reductions. This is in agreement, within the aperture sizes used, with the radial brightness distribution in visual images of Comet Bowell obtained by Larson (personal communication). As we can see the comet's brightness varied through the observing period, being brightest on the last and first night of observations.

TABLE 4.

COMET BRIGHTNESS AT K (2.2 μm)

Date	K Mag	Aperture	Telescope	K Mag for an 11.5" Aperture	R	Δ	Scattering Angle
4/10/81	12.44	11.5"	61"	12.44	4.6	3.6	177°
4/25/81	12.98	8.7"	MMT	12.67	4.5	3.6	173°
5/10/81	12.74	11.5"	61"	12.74	4.4	3.7	171°
5/15/81	12.68	7.8"	90"	12.25	4.4	3.7	169°

Discussion

The data obtained allow constraints to be put on the kind of material producing the scattered light from the comet. We have worked under the assumption that a major component of the grains in the coma is frozen water, and have modeled the scattering particles to match the observations. The justification of such an assumption is based on the following observations:

a) The presence of a hydrogen and OH coma detected in all comets observed in the UV. This coma has been shown by Keller and Thomas (1975) to be the photodissociation product of H_2O. The production rate of OH is roughly two orders of magnitude larger than that of any other observed radical species.

b) The identification of H_2O ice as controlling the vaporization process in most comets (Delsemme and Rudd 1973).

c) The tentative detection in comets of H_2O^+ by Herzberg and Lew (1974) and of H_2O by Jackson, Clark, and Donn (1976) and Corvisier et al. (1981).

d) The disappearance of the 10-μm silicate emission feature in comets at heliocentric distances of about 2 AU (Rieke and Lee 1974). Rieke (1977) points out that this disappearance correlates well with the expected stability of clathrate hydrate grains which may act as glue holding the silicate grains in clumps too large to show the 10-μm feature.

Despite the expected abundance of water in the grains of Comet Bowell, our observations do not show water frost absorption features at 1.5 and 2.0-μm in the reflectance spectrum. This result can be explained in at least two ways (Hanner 1981): 1) scattering by predominantly small particles, and 2) masking due to dirty ice or core-mantle grains. In the case of Comet Bowell small particles do not seem to be abundant. The absence of evidence for Rayleigh scattering means that the particles are larger than about 0.3 μm. Furthermore, Sekanina (1982) concludes from a dynamical analysis that the coma particles are sub-millimeter size and larger. Hanner (1981) also states that amorphous ice will exhibit broadened features which are not as deep as in the crystalline phase and therefore harder to detect. This difference, however, seems to be subtle and not easily detectable except in high signal-to-noise spectra (Fink and Sill 1982). The case in which the coma is populated by 2 different types of particles, pure ice grains and pure dust grains, is ruled out. This is because the high albedo of pure ice requires that the dust particles be several times more abundant than the ice ones in order to scatter a computable amount of light, which is not the case even in the dustiest of comets. Therefore I choose the masking due to dirty ice or core-mantle grains as the most likely cause for the absence of the 1.5 and 2.0 μm-bands.

Based on the conclusion stated above Mie scattering models have been generated of water frost grains of different sizes and with different amounts of an absorbing contaminant and with the same scattering angle as the comet. The contaminant has been chosen to have wavelength independent absorption over the region of interest (1 to 5 μm). This assumption is justified considering that most of the likely contaminants (i.e. cosmochemically common materials like graphite or magnetite) have featureless reflectance spectra in this region (Huffman and Stapp 1973; Huffman 1977). Pure silicate contaminants, as explained below, are not favored by the models because of their high albedos.

The observations allow the restriction of the models to two cases: a) pure ice particles small enough not to show the 1.5 and 2.0 μm bands but large enough not to Rayleigh scatter; and 2) large dirty in which the contaminant masks the absorption features. An example of the first case is given in Figure 11, where the observations are compared to the scattering by pure ice grains 0.5 μm in radius. The observations could not be matched even by a broad distribution of particles in this size range.

The best fit to the observations, which is shown in Figure 12, is obtained with a model of the second category: particles 10 μmin radius and larger with imaginary index of refraction n" = 0.05 and albedo near 5%. To illustrate how much the spectrum can vary with only a small reduction in the "dirtiness" of the particle, Figure 13 has been added. In this figure, particles of the same size as Figure 12 were used, but the n" was reduced by a factor of two.

Our model is in excellent agreement with the 6% geometric albedo of the particles in Comet Bowell determined from infrared reflected and thermal observations by Hanner, Veeder and Matson (1981)

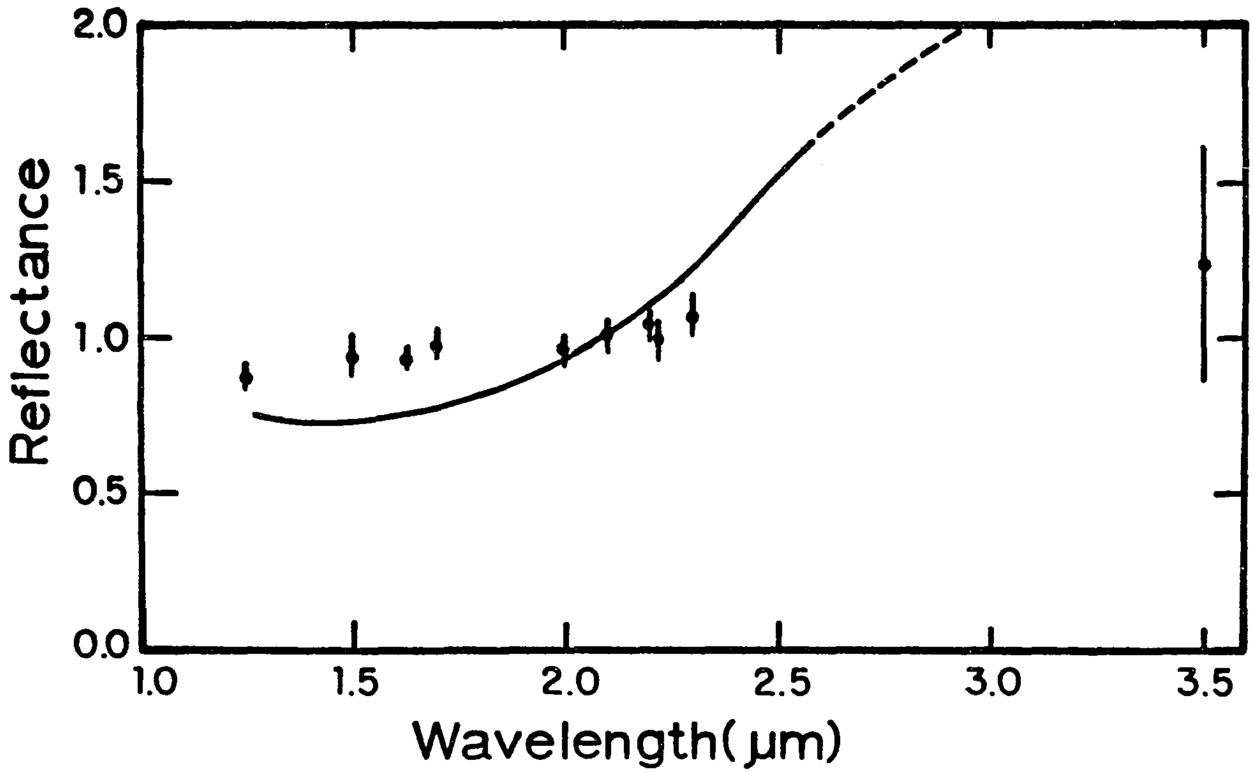

Figure 11. Scattering by pure ice particles of 0.5 μm in radius, compared with the 1981 observations of Comet Bowell.

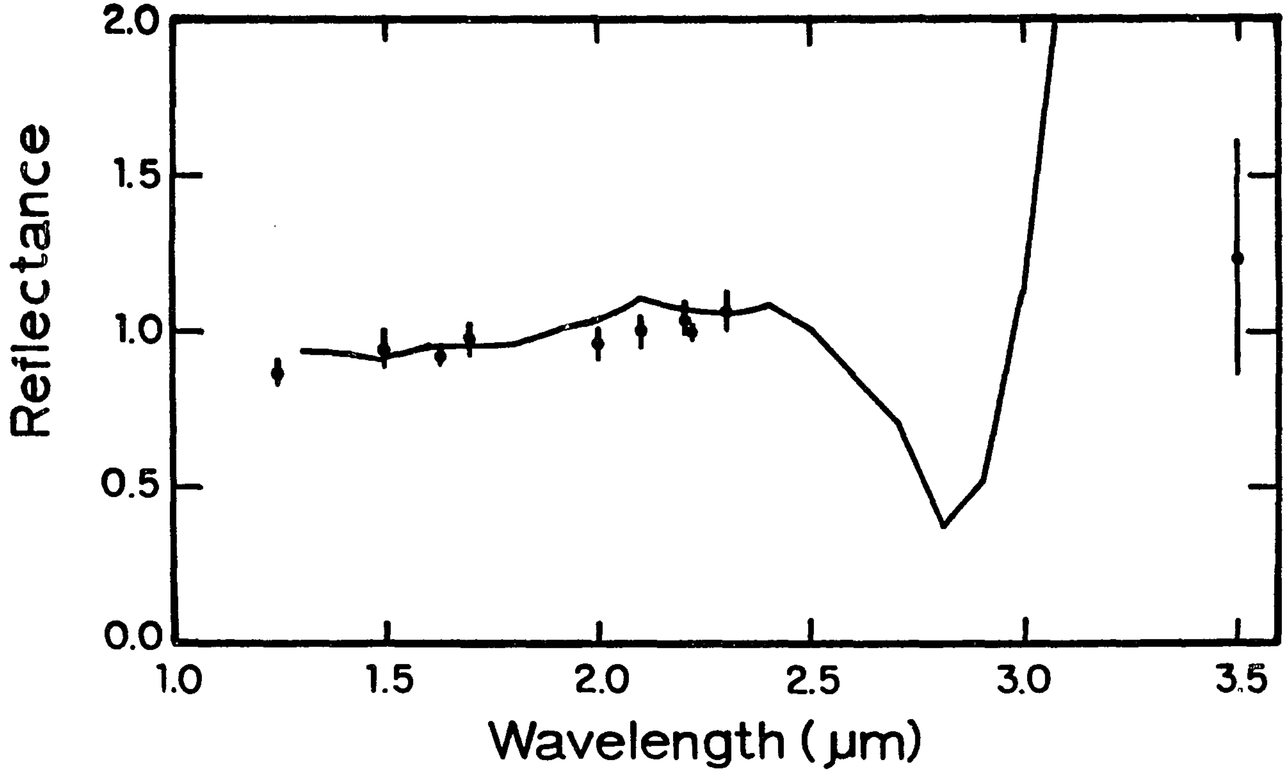

Figure 12. Scattering by dirty ice particles of 10 μm in radius with n" = 0.05, compared with the 1981 observations of Comet Bowell.

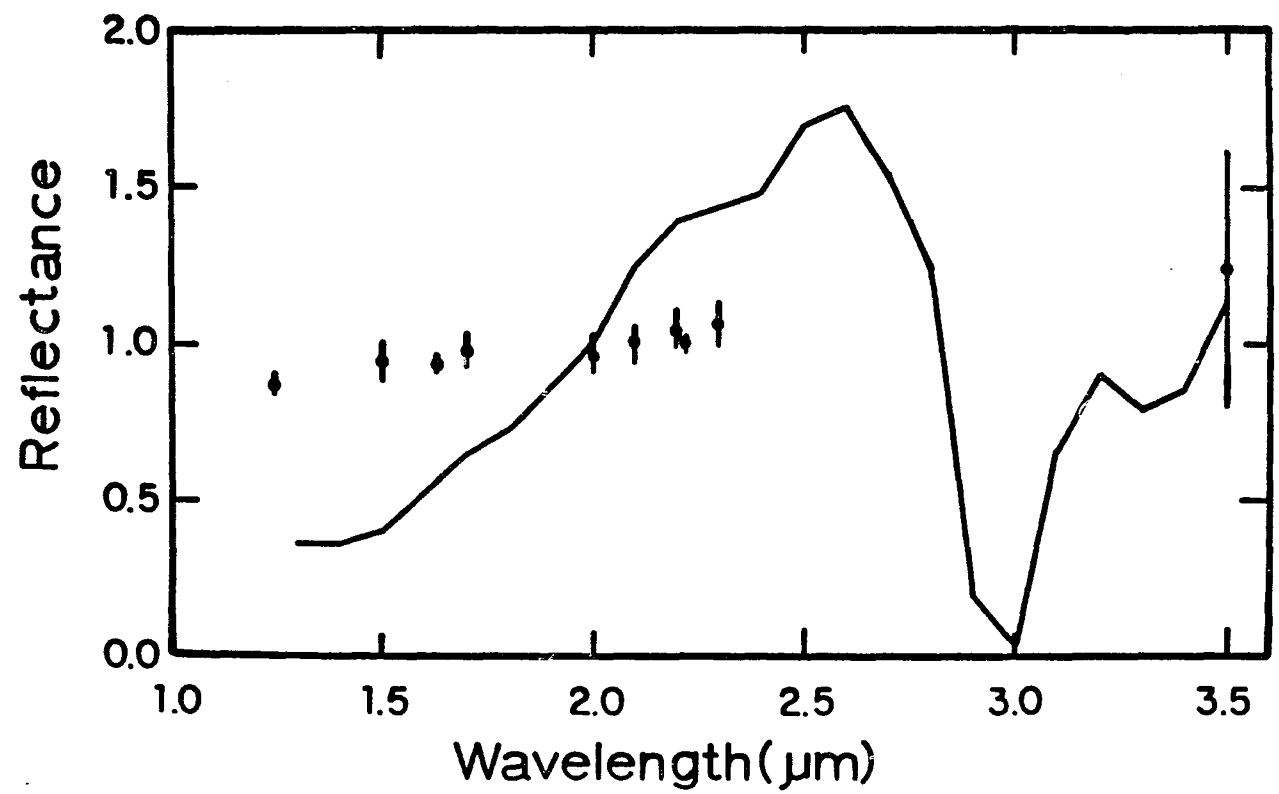

Figure 13: Scattering by dirty ice particles of 10 μm in radius with n" = 0.025, compared with the 1981 observations of Comet Bowell.

and Jewitt et al. (1982). How to make a frost grain so dark is our next problem. According to Clark (1981), if the contaminant is carbon soot, only 0.1 weight % of a = 0.1-μm grains of it in pure frost grains of a = 1 mm will reduce the reflectance to that of the soot itself. Clark also observed that as the frost particle size decreases, the amount of soot necessary to reduce the reflectance to the same level increases roughly proportional to the decrease in frost particle size. The opposite effect was observed for the soot particle size.

Based on Clark's observations one can visualize how a very small amount of an extremely fine grained dark contaminant well mixed with the frost can bring the albedo down to the values modeled and observed. This, however, is the extreme lower limit. Our knowledge of the characteristics of the dust in other comets permits us to construct a more realistic picture of the icy grains in Comet Bowell. As mentioned earlier, the behavior of the infrared emission from a number of bright comets has led Campins and Hanner (1982) to a general two-component model of the dust: an absorbing component (typified by magnetite) and a silicate component (typified by amorphous olivine). In the case of Comet Bowell the absorbing component probably plays the role of the dark contaminant material, since silicates have almost no absorption at visual wavelengths. Pure silicate dust mixed with water frost will reduce the depth or completely mask the 1.5 and 2.0-μm bands, but without lowering the albedo significantly; whereas observations of a number of comets show typical average albedos to be only 10-15% (Ney 1982; and Chapter 5). The size range of the dust grains can be constrained from observations of comets near the sun, where the particles are warm and devoid of ices. The absence of Rayleigh scattering in all comets observed to date implies that $a > 0.3$ μm. The presence of the 10-μm silicate emission feature in most comets observed indicates grains with $a < 10$ μm. Grains with a size distribution given earlier in this chapter, which peaks around 1 μm, were found to fit the thermal continuum at 3.5 and 4.8 μm of all comets for which data are available.

Using Clark's (1982) observations, we have calculated the minimum weight % of contaminant needed to bring the geometric albedo of the frost grains down to the value modeled and observed in Comet Bowell, assuming the absorbing grains observed in comets near the sun are as effective in reducing the the albedo as were the carbon soot particles in Clark's samples. Two contaminant particle sizes were used, 1 and 10 μm; these represent the typical and upper limit radius for the dust in comets near the sun. The frost grain size of 0.1 mm which we have chosen is one used by Clark and is also in the size range for Bowell's coma particles derived by Sekanina (1981). For 1 μm the weight % of contaminant is 1 and for 10 μm its 10. It is encouraging that these lower limits do not violate the solids/H_2O ratio for five comets given by Ney (1982).

We are led then to the following picture of the icy grains in comets at large heliocentric distances: A volatile matrix composed mostly of frozen H_2O (crystalline or amorphous) with embedded dust grains composed of a mixture of absorbing and silicate materials. The dust particles are roughly micron sized; the size of the whole grain is about 1 to 3 orders of magnitude larger than that of the dust grains. In this picture, the dust particles are released as the larger, (low albedo) icy grains, sublimate heated by sunlight. This model explains the disappearance of the silicate feature in Comet Kohoutek (1973f) beyond about 2 AU, and why this change was not accompanied by a higher albedo of the coma particles (Rieke 1977).

Because the 3.1-μm frost band is so much stronger than the 1.5 and 2.0 μm ones, and because other volatile species like NH_3 and CO_2 also have deep bands near 3 μm, this area of the near infrared spectrum is the most diagnostic of the presence of frozen volatiles. In fact, our theoretical models of icy grains invariably showed a prominent feature around 3 μm. This feature was present for all particle sizes modeled (0.5 μm and up) and for all levels of dirtiness (pure ice to ice with $n'' = 0.05$). At the brightness of Comet Bowell during these observations, we were unable to search successfully for absorption features near 3 μm; in 1982, an absorption was present.

Our model of the icy grains has an important implication on the surface characteristics of cometary nuclei: they are low albedo objects. In the most widely accepted model a comet nucleus is an undifferentiated aggregate of ice and dust with only small scale inhomogeneities (Donn and Rahe 1982; Delsemme 1982). Considering this model and the sublimation model described by Delsemme (1982), it seems safe to assume that at large heliocentric distances there is no preferential ejection of dark particles into the coma. The coma particles may be depleted in the volatiles which fuel the cometary activity at low temperatures; however, since water seems to be the major volatile component of these grains, one would not expect this depletion to change drastically either the composition or the albedo of the particles being ejected from the nucleus. On the contrary it has been suggested (Whipple 1950) that large nonvolatile particles will not be carried away by the gasses, forming a layer on the nucleus (which may make it even darker than the coma particles). This layer may be blown off by outbursts. In the case of Comet Bowell the coma particles are not volatile-poor (see next section) furthermore in a new comet such as Bowell we expect these particles to be volatile rich since the comet has not undergone periods of high activity which would form such a layer of refractory material.

We can then picture a dark comet nucleus with an albedo close to that of the icy grains. According to this model, if the dust in Comet Halley is as dark as that in Comet Bowell, then its nucleus is likely to have a geometric albedo of approximately 5 to 10%. This is in agreement with the upper limit to the geometric albedo of the nucleus of Halley estimated by Belton and Butcher (1982) who were unable to detect it at a limiting magnitude of 24.3 at 12 AU.

There are limitations to the use of Mie scattering models to simulate the cometary particles. The grains in the coma of comets are likely to be highly irregular. However, the departure from sphericity seems to affect mainly the polarization and the shape of the scattering function. The position of absorption bands is not at all affected by the irregular particle scattering and their depths seems to be changed only slightly (Tomasko, personal communication).

We now turn to the variability in the brightness of the comet. Normally a comet undergoes changes in its brightness of different amplitudes and timescales as a result of the activity in the nucleus. According to Sekanina (1982), Comet Bowell was in a dormant phase until early 1981. The rapid increase in brightness observed May 15 indicates that the comet entered an active phase near that date. Sekanina (1982) has also suggested a very low ($\sim$1 m/sec) grain velocity with respect to the comet nucleus and that the grains contained little material that is volatile at the heliocentric distance of the comet in 1981. At the time of our observations, our beam had a projected radius of $\sim 3 \times 10^4$ km at the comet; therefore the oldest grains in our beam would be approximately one year old. Under these conditions, the rapid reduction in brightness between April 10 and 25 would be difficult to understand. The possibilities that the grain velocities are > 10 m/sec and that the activity of the comet is fueled by a very volatile component need further consideration.

Second Program

A year later Comet Bowell was about 1 AU closer to the sun and the earth and about one magnitude brighter. At this time priority was given to observations in the 3 μm area which had not been possible the preceding year. A strong absorption was found near 3 μm in the spectrum of this comet. The detection is the result of 3 nights of observation with the University of Arizona 1.54-m telescope and 1 night with the NASA Infrared Telescope Facility in Hawaii, using a filter centered at 3.25 μm with a bandpass of .45 μm. Standard K photometry (2.2 μm) was interlaced with the longer-wavelength measurements to define the shorter wavelength continuum. The comet was observed on April 23, June 11, and June 13 UT from Arizona and on June 22 UT (all 1982) from Hawaii. Through this period the comet was between 3.4 and 3.5 AU from the sun and 2.9 and 2.6 AU from the earth. 58 Ophiucus, a solar type star (F7 IV), was used as a nearby comparison to determine the slope of the solar spectrum. The comet was measured through a 11.5 arcsec diameter aperture with reference beams 14 arcsec east and west of the nucleus from Arizona and 7.8 arcsec aperture and reference beams 9 arcsec to the north and south from Hawaii. All four measurements set show the albedo at 3.25 μm to be significantly lower than that at 2.2 μm; the combined result is that the albedo at the longer wavelength is 0.52 ± 0.06 times that at the shorter one.

This measurement is plotted in Figure 14 along with the previous spectrophotometry near 2 μm; all of the measurements are normalized to the brightness at 2.2 μm. It is expected, as explained above, that the contaminants in the ice particles will bring the geometric albedo of the particles down to about 5% and will suppress

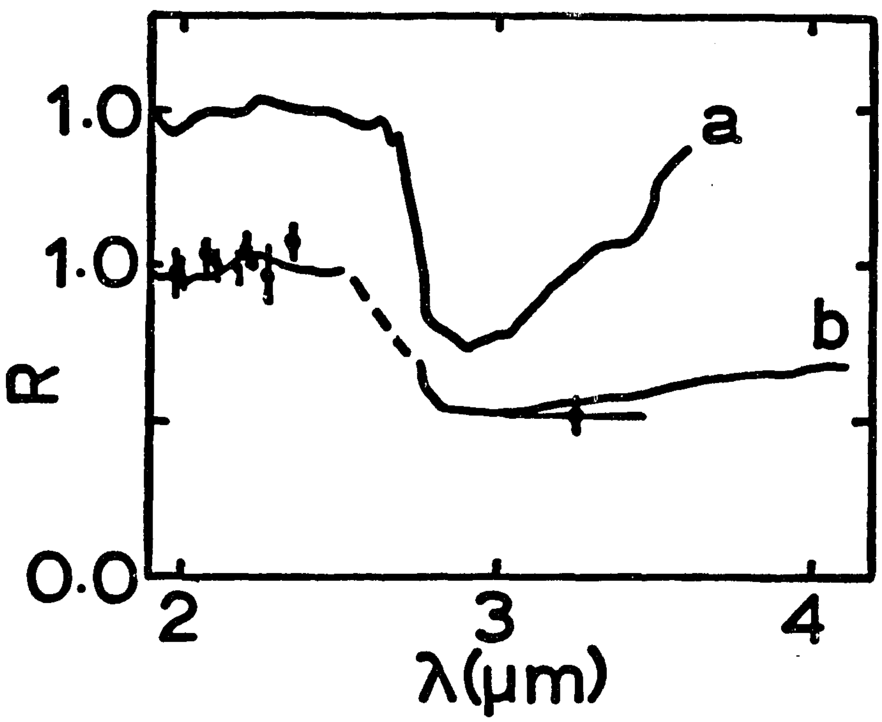

Figure 14. Relative reflectivities (R) of Orgueil (a), Callisto (b), and Comet Bowell (points). For clarity, the spectrum of Orgueil has been displaced upward by 0.5 in R. All three reflectivity curves have been normalized to 1.0 at 2.2 μm.

the 1.5 and 2.0-μm bands, but that the stronger 3 μm one could still be present. As an illustration of this possibility, the spectrum of Callisto is shown, which has absorption features thought to arise primarily from water frost (Lebofsky, personal communication). Note that the low surface reflectivity of Callisto has substantially decreased the relative strength of the 2.0-μm frost band in the spectrum, but a well defined band remains between 3 and 4 μm.

The measurements reported here are consistent with those of Comet Bowell by A'Hearn (personal communication) made from the IRTF on April 27-30, 1982. They found the albedo at 3.45 μm (bandpass 1.05 μm) to be depressed relative to the continuum at H (1.6 μm) by about 20 to 40% and the albedo at 3.8 μm (bandpass 0.67 μm) to be depressed by about 15 to 45%.

Of the ices which are likely to be found in comets, H_2O, NH_3, H_2S, and CH_4 have absorption features near 3 μm (Fink and Sill 1982); however, only H_2O is a plausible identification at the heliocentric distance at which Comet Bowell was when observed (3.4 AU). From dynamical considerations, it is believed that the grains in this comet are $\geq$ 0.5 mm in diameter (Sekanina 1982). The grains have a geometric albedo of only about 6% which will make their temperature approximately equal to that of a rapidly rotating blackbody in equilibrium with the absorbed solar radiation, at 3.4 AU this temperature is about 150 K. Under these conditions, it can be shown (Lebofsky 1975) that the lifetimes against evaporation are respectively 1.4 years and 12 seconds for H_2O and NH_3 ice grains; the other candidate ices are even more volatile than NH_3.

These lifetimes can be compared to the time it would take a particle to travel from the nucleus of the comet to the radius included in our largest aperture (2×10^4 km). The grain velocity with respect to the nucleus in this comet is though to be about 1 m/sec (Sekanina 1982), which means that the oldest grains in our beam are about 0.7 years old. Therefore , H_2O grains are stable enough to have produced the observed absorption, but all other candidate ices are too volatile by orders of magnitude. This still holds for grain velocities as high as thousands of km/sec, quite unlikely in comets±

Another possibility is that the absorption near 3 um is due to water of hydration in the cometary grains, as is observed in some asteroids (Lebofsky et al. 1981). As an example, in Figure 14 we have plotted the spectrum of the meteorite Orgueil (Larson et al. 1979), a CI carbonaceous chondrite with about 20% water (by weight) in the form of hydrated minerals. Although the bands due to water of hydration are usually narrower than those due to ice, the data presented here cannot distinguish between these two cases. However, as mentioned above the A'Hearn's data (personal communication) indicate that the albedo of the Comet Bowell grains is slightly reduced at 3.8 um relative to the shorter wavelengths, in support of our interpretation that the band is due to frosts. In addition, the ratio of mass loss of H_2O gas to mass loss of solids (i.e., gas to dust ratio) for five comets at small heliocentric distances has been estimated to range from about 1.6 to

10 (Ney 1982). This ratio is, therefore, much larger than is typical for hydrated minerals; since it probably reflects the composition of the grains before they lose volatiles, we conclude that the grains at large heliocentric distance are composed mostly of water.

The detection of ice in cometary grains provides one of the strongest possible confirmations of Whipple's (1950) icy conglomerate model of cometary nuclei. It also supports a broad range of theoretical arguments that water should be the dominant parent molecule for some of the gasses detected by spectroscopy of comets. Two recent illustrations are: 1) Spinrad (1982) has derived the oxygen production rates for nine comets for observations of [OI] lines. These production rates are in agreement with H_2O being the sole parent molecule and are in agreement with H_2O production rates derived from IUE observations; and 2) OH has been detected in emission in Comet Bowell, both through groundbased and IUE observations (Feldman et al. 1982). The OH coma of comets is thought to be the photodissociation product of H_2O (Keller and Thomas 1975).

CHAPTER 5

PERIODIC COMETS

Those comets with periods shorter than 200 years are called periodic, those with greater periods are considered nonperiodic comets. Periodic comets tend to be intrinsically fainter and smaller than nonperiodic comets, probably due to the loss of mass after repeated perihelion passages. Dynamical and physical processes will inevitably reduce the population of periodic comets. The capture of nonperiodic comets by Jupiter produces periodic comets with direct and low inclination orbits. This capture is the main source of replenishment which maintains the population of periodic comets.

Most infrared observations of comets have been directed at bright easily observable nonperiodic comets. Until recently the only infrared observation of a periodic comet was that of Encke by Ney (1974). We present nearly simultaneous photometric observations of the reflected and thermal regions of the spectra of five periodic comets. These data allow the first detailed comparisons of the properties of the dust in periodic comets with that in nonperiodic ones.

Observations

Comet P/Chernykh was observed in October of 1977, and Comets P/Encke, P/Stephan-Oterma, and P/Tuttle were observed in the fall of 1980. Comet Kearns-Kwee was observed in December 1981 and January 1982. The observations are summarized in Table 8. They were made

TABLE 5.

SUMMARY OF THE INFRARED OBSERVATIONS

Comet	Date (UT)	r (A.U.)	Δ (A.U.)	J	H	K	L	M	N	<10.4/N>	Q
Cherynkh	10/13/77	2.76	1.77	----------	----------	----------	----------	----------	5.76±0.21	0.36±0.07	----------
	10/15/77	2.76	1.77	----------	13.65±0.04	13.65±0.01	----------	----------	5.82±0.19	----------	----------
Encke	10/10/81	1.23	0.45	----------	15.20±0.16	----------	----------	----------	----------	----------	----------
	10/12/80	1.20	0.43	----------	----------	----------	----------	----------	3.71±0.10	----------	----------
	12/2/80	0.36	0.87	10.46±0.09	10.19±0.03	9.77±0.04	6.38±0.00	4.60±0.01	1.93±0.05	0.45±0.02	----------
Kearns-	12/3/81	2.22	1.33	14.10±0.03	13.81±0.03	13.46±0.04	----------	----------	----------	----------	----------
Kwee	1/16/81	2.25	1.31	----------	13.72±0.09	----------	----------	>8.9±(3σ)	----------	----------	----------
	1/17/82	2.26	1.32	----------	----------	----------	----------	----------	5.18±0.30	----------	----------
Stephan-	10/10/80	1.73	0.96	12.81±0.06	12.61±0.06	12.47±0.01	----------	----------	----------	----------	----------
Oterma	10/12/80	1.72	0.94	----------	----------	----------	----------	----------	3.63±0.06	0.39±0.03	----------
	12/2/80	1.58	0.60	11.44±0.02	10.95±0.01	10.81±0.03	----------	----------	----------	----------	----------
	12/3/80	1.58	0.60	----------	----------	----------	----------	8.54±0.13	2.32±0.01	0.43±0.03	-0.38±0.11
Tuttle	12/2/80	1.03	0.49	----------	12.04±0.02	11.72±0.06	----------	----------	----------	----------	----------
	12/3/80	1.02	0.49	----------	----------	----------	----------	6.37±0.07	1.93±0.01	0.43±0.01	----------

N, λ_{eff} = 10.6 μm; FWHM - 5.1; 10.4 narrow band, FWHM = 1.3 μm.

with the Catalina 154-cm telescope of the University of Arizona, using the infrared observational techniques and calibration described by Low (1973) and Low and Rieke (1974) (Chapter 2). The Chernykh observations and the October observations of comets Encke and Stephan-Oterma were made with 8.5 arcsec apertures. All the other observations were made with an 8.5 arcsec aperture shortward of 5 μm and a 10 arcsec aperture longward of 5 μm. The comae of all the comets were larger than the apertures used. A brightness proportional to the diaphragm diameter is assumed with corrections for the aperture size are made to combine reflected and thermal observations. All measureλλments are relative to reference areas approximately 11 arcsec to the east and west of the comet nucleus.

Discussion

The observations of these five periodic comets were made similarly to those of Comet Kohoutek (1973f) by Rieke and Lee (1974). Below is a discussion of the properties of the dust in these comets as derived from the observations. In general the dust in the periodic comets seems to be similar to that in Comet Kohoutek; however, Comet Encke showed some interesting peculiarities.

J H K Colors

Table 6 gives the J, H, and K (1.25, 1.63, 2.22 μm) colors of the comets observed; also given are the solar J H K according to Johnson et al. (1975). These colors are similar to those observed in nonλλperiodic comets. The J, H, and K magnitudes of Comet Stephan-

TABLE 6.

J H K COLORS

Comet	J - H	H - K
Solar	0.30	-0.05
P/Chernykh (10/17/77)	-----	0.00 ± 0.11
P/Encke (12/2/80)	0.27 ± 0.09	0.42 ± 0.05
P/Kearns-Kwee (1/1/7/82)	0.29 ± 0.04	0.35 ± 0.05
P/Stephan Oterma (10/10/82)	0.20 ± 0.08	0.14 ± 0.06
P/Stephan-Oterma (12/2/80)	0.49 ± 0.02	0.14 ± 0.03
P/Tuttle (12/2/80)	-----	0.32 ± 0.06

\

Oterma at r = 1.73 AU were recalculated correcting for a small systematic error. They differ slightly from those reported in a previous work (Campins et al. 1981).

The absence of Rayleigh scattering indicates that small particles (radius <0.3 μm) are not very abundant in the comae of these comets. The slightly blue J-H color of Encke observed when the comet was at 0.36 AU from the Sun may be due to the presence of the CN emission mentioned in Chapter 3. This is rather likely since the comet showed very strong CN emissions in the visible on November 4th, 1980, when observed by S. Larson (personal communication). The J-H color of Stephan-Oterma at 1.73 AU may indicate a difference in mean particle size or composition or merely the effect of scattering angle. The very red H-K of Encke is due to thermal emission contributing to the K flux.

Even though JHK observations are useful in determining albedos and dust production rates, they are not by themselves good indicators of the composition of the scattering particles (Hanner 1981).

Thermal Curve

Color temperatures were calculated using the N-M (10.6/5.0 μm) color index and using both the N-M and M-L (5.0/3.5 μm) for Encke at r = 0.36 AU (Table 7.) The contribution to the N flux from the 10-μm silicate emission feature was subtracted. [The feature was assumed to have the same shape as that observed in Comet Kohoutek by Merril (1974) and had an equivalent width of 5.6×10^{12} Hz in Encke, 4.6 x

TABLE 7.

TEMPERATURES

Comet	r (A.U.)	Color Index	T (°K)
P/Encke	0.36	N-M	473
P/Encke	0.36	M-L	550
P/Stephan-Oterma	1.58	N-M	235
P/Tuttle	1.03	N-M	300

10^{12} Hz in Tuttle, and 3.4×10^{12} Hz in Stephan-Oterma]. The M-L color index avoids the spectral regions where emission bands are known to occur. The N-M color temperatures run slightly (2-9%) above the temperature of a rapidly rotating blackbody at the same heliocentric distance. The M-L color temperature of Encke, however, is about 18% higher than the blackbody temperature and 16% higher than the N-M color temperature. As we can see the color temperature depends on the color index used. This is expected when a particle size distribution rather than single-sized particles are responsible for the thermal emission, the small particles being hotter than the larger ones because they radiate less efficiently at wavelengths much larger than their size.

Campins and Hanner (1982 and Chapter 4) show that the M-L color index of Encke falls very close to a model which fits the variation with heliocentric distance of the M-L color index of Comet Kohoutek.

The presence of a 10-μm silicate emission feature can be determined by comparing the 10.4-μm narrowband flux with the broadband N flux (Lebofsky and Rieke, 1979). A value of 0.35 is expected for a featureless thermal spectrum and is not very sensitive to temperature in the range considered here. As indicated by the values of (10.4/N) in Table 8, Comets Encke, Stephan-Oterma, and Tuttle showed a strong feature at the time of the December observations, which was very close to the perihelia of these three comets. At marginal signal to noise,

TABLE 8.

ALBEDOS

Comet	r (A.U.)	Albedo	Scattering Angle
P/Chernykh	2.76	0.05 ± 0.03	180°
P/Encke	1.21	0.02 ± 0.01	131°
P/Encke	0.36	0.33 ± 0.02	86°
P/Kearns-Kwee	2.26	0.16 ± 0.05	170°
P/Stephan-Oterma	1.73	0.10 ± 0.03	151°
P/Stephan-Oterma	1.58	0.14 ± 0.02	172°
P/Tuttle	1.03	0.10 ± 0.02	110°
Kohoutek* (1973f)	1.25	0.15 ± 0.02	145°

*From Rieke and Lee (1974)

the feature was absent both in Comet Chernykh and in Comet Stephan-Oterma at r = 1.73 AU. This behavior agrees with the finding by Rieke and Lee (1974) that silicate emissions were absent in the spectrum of Comet Kohoutek for r > 1.7 AU. No 10.4-μm observation of Comet Encke was obtained at r= 1.20 AU.

Albedo

The dust grains in the coma seem to be composed of a mixture of at least two materials; Campins and Hanner (1982) concluded that in Comet Kohoutek an absorbing material like magnetite is needed to explain the change in the thermal continuum with heliocentric distance and a silicate component like amorphous olivine to account for the 10- and 18-μm features. Their arguments followed the method outlined in Chapter 3 and are discussed in more detail in Chapter 4.

The presence of both hot absorbing grains and cooler silicate grains means that the albedo derived from the relative strength of the thermal and the scattered radiation (i.e., using Equation 4) may not refer uniquely to one component.

Nevertheless, it is possible to make a qualitative comparison among the comets observed by calculating their albedos using Equation 4 and correcting for the scattering angle dependence of the albedo by using the scattering function obtained for five comets by Ney (1982). The results are given in Table 8. The albedo for Comet Kohoutek from Rieke and Lee (1974) is included for comparison.

Except for Comets Encke and Chernykh, all other comets have an albedo between 10 and 16%. The large uncertainty in the case of P/Chernykh is due to the fact that the only thermal observation of the comet that could be obtained was not around the expected peak of the comet's thermal curve, leading to a larger uncertainty in the determination of the total energy reradiated. Comet Encke, on the other hand, was studied much more thoroughly and shows significant differences from the other comets.

Comet Encke

The behavior of this comet deserves special attention. The 2% albedo calculated from the October observations is unusually low for any comet; on the other hand, the 33% albedo obtained from the December observations is larger than the typical albedo for other comets (see Ney, 1974b, 1982).

As previously mentioned the albedo obtained using O'Dell's method may not be the actual albedo of the scattering particles. It must be pointed out, however, that P/Encke was observed in the exact same manner as the other comets discussed in this work, so there is little doubt that such a radical change in the observed albedo indicates a peculiarity in the characteristics of the dusty component of Comet Encke. Only one other comet, Bradfield 1974b, has shown a sudden change in the albedo of its dust (Ney, 1974). The change in Comet Bradfield, however, was also accompanied by a loss of the silicate feature and most of the dust coma, which was not the case in Comet Encke.

P/Encke's albedo was calculated under the assumption that the scattering function observed by Ney for other comets also applies to Encke. One possible explanation for the albedo change is that the particles the comet was ejecting at r = 0.36 AU had indeed a higher albedo than those ejected at r = 1.2 AU. Another possibility is that it is an artifact of the use of this scattering function, in which case finding the appropriate function may help determine the nature of the particles.

Conclusions

The peculiar changes in the infrared spectrum of Comet Encke indicates that the albedo and/or the scattering function of the dust particles in this comet are not only different from other comets but may also be a different function of heliocentric distance. The available observations of periodic comets indicate a wider range of dust albedos than that observed in nonperiodic comets, however, most of the other characteristics of the dust (size range, silicate emission feature, etc) are rather similar in both types of objects.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Infrared observations of comets have revealed new information about the solid particles in the coma as well as in the nucleus. Following is a summary of the characteristics of cometary solids derived from, or confirmed by, the observations presented in this work. These characteristics will then be used to infer the structure of cometary nuclei. The relation between cometary and interstellar dust suggested by the obsrvations will be considered. Finally a speculative hypothesis on the formation site of comets is presented.

Characteristics of Cometary Solids

The understanding of the nature of cometary solids is of great signficance to the understanding of the nature of comets themselves. All of the information we have about cometary solids comes from observations of particles in the coma. The characteristics of the particles observed in comets at small heliocentric ditances are summarized as follows:

1) Cometary grains are composed of at least two types of material: an absorbing material (typified by magnetite) which explains the behavior of the thermal continuum, and a silicate material (typified by amorphous olivine) to fit the 10- and 18-μm emission features.

2) The size distribution of cometary dust as derived from the behavior of their thermal continuum (Chapter 4), and from their scattering properties (Chapters 4 and 5), does not vary drastically from comet to comet. This distribution is generally restricted to the range between 0.3 and 10 μm and peaks around a few microns.

As discussed in Chapter 4, at large heliocentric distances (> 2 AU) cometary particles look very different; in the case of Comet Bowell these particles were icy grains with diameters $\geq$ 0.5 mm. The direct detection of water ice in Comet Bowell supports very strongly Whipple's icy conglomerate model by confirming the presence in comets of frozen volatiles.

Structure of the Nucleus

Having establised what some of the main components of the nuclear material are, I will discuss next the small ($\sim$1 mm) and large (several km) scale structure of this material.

Small Scale

Considering the sublimation model of the nuclear ices described by Delsemme (1982), it seems safe to assume that the grains observed in the coma of comets at large heliocentric distances closely resemble the nuclear material.

The grains in Comet Bowell had a volatile matrix composed of mostly water ice with embedded dust grains like those described above, which give the whole grain an albedo roughly equal to that of the dust grains themselves (about 5% in the case of Bowell). The icy grains are stripped from the nucleus by the sublimation of more volatile ices like NH_3, CO_2, or CH_4, which control the activity of the comet at large heliocentric distances. As was the case of water until its detection in Comet Bowell, the presence of these ices has never been directly determined, but it is inferred, in the case of Bowell, by the short timescale variability in the brightness of the comet.

According to this picture, the dust particles are released as the larger icy grains sublime heated by sunlight. This model explains the disappearance of the silicate features in Comets Kohoutek and West beyond about 2 AU, and why this change was not accompanied by a higher albedo of the coma particles.

The recent recovery of Comet Halley at a magnitude of 24.2 at 11 AU (Jewitt and Danielson 1982), suggests a very low albedo for the nucleus of about 10 to 15%, in agreement with the albedo expected if the dust in Halley is as dark as that in Comet Bowell.

Large Scale

The evidence in favor of the undifferentiated nature of cometary nuclei was summarized in Chapter 1. Further evidence in support of this model is found in a comparative study of the dust in periodic and nonperiodic comets, in the albedo of icy particles and in the behavior of Comet West as it split.

In Chapter 5 the characteristics of the dust in periodic comets were discussed. It was concluded that, even though the periodic comets showed a wider range in grain albedos, the dusty component in periodic comets did not differ radically from that in nonperiodic comets. Furthermore the analysis of the thermal continuum of 6 comets, ranging from "new" to periodic, showed striking similirities in the behavior of all comets. Since both of these types of comets seem to have a common origin, the observed similarities in their dust suggests that their dust content is the same throughout the nuclei of comets and that aging does not alter the characteristics of the solids ejected.

The existence of dark icy particles and of a dark icy nucleus is consistent with the nucleus being a very pristine undifferentiated body. A fairly homogeneous mixture of ices and dust which accretes in the nebula is expected to have a low albedo for reasons explained in Chapter 4. Differentiation would produce a rocky core and an icy mantle. The surface of such a body may be darkened by some other mechanism (i.e., bombardment) but will otherwise have a high albedo. This could be the case for 3 of Jupiter's satellites. Europa, Ganymede and Callisto are all made of a mixture of ices and rock. Europa and Ganymede have undergone differentiation, probably due to tidal heating, their geometric albedos are about 0.55 and 0.40, respectively. Callisto, on the other hand, free of tidal forces is less differentiated, it has the lowest albedo, about 0.17. Phoebe, Saturn's outermost satellite, may be another example of a very primitive body of very low albedo. This object, probably captured, has a geometric albedo of 0.06. It has a small radius of about 100 km and it is likely to have escaped the bomλλbardment that led to the fragmentation of Saturn's inner satellites, so it is expected to be the most primitive body examined from a spacecraft.

Comet West is a very special case in which evidence for large scale homogeneity (in the sublimation pattern of each fragment) and for small scale differentiation (in the silicate spectra of the different fragments) was observed in the same comet. These observations suggest that the nucleus of this comet did not have an "onion skin" or layered structure but rather had pockets containing dust grains with different size distributions which were ejected as the ices around them sublimed. As suggested by Rieke (1977), this would explain not only the variability in the silicate spectra, but also the bands and streamers in the tail which were probably the result of the exhaustion of different pockets of dust grains. Such a structure of the cometary nucleus is predicted by a model for cometary accretion described by Donn and Rahe (1982).

It has been suggested that ^{26}Al was present in early solar system condensates in sufficient abundance to melt the interiors of minor bodies as small as comets (Lee and Papanastassiou 1974). The observational evidence discussed, as well as the formation mechanism proposed, do not support such melting occuring in comets. Furthermore, since most meteorites (Chondrites) do not show any evidence of having melted (except for the chondrules in some of them) probably the ^{26}Al was not as abundant (or no longer active) during accretion to produce the necessary heat. Therefore it is reasonable to conclude that comets could have very easily escaped melting.

Relation between Cometary and Interstellar Dust

The similarity of the 10- and 18-μm cometary features with those of the interstellar medium supports a number of observational and theoretical arguments that cometary dust is not a nebular condensate but rather has a presolar origin. Cameron (1973), Biermann and Michel (1978), and Greenberg (1982) propose that comets formed as aggregates of interstellar matter at almost interstellar distances. Most accepted, however, is the idea of an origin in the planetary region, since it is in agreement with theories of planetary formation suggesting that a large number of planetesimals were scattered by the giant planets in the late stage of their accretion (Fernandez and Jockers 1982). If one adopts the cometary origin in the planetary region, the interstellar origin of the cometary dust is still very appealing since there is evidence that the nebula was not hot enough to vaporize all presolar grains (The isotopic anomalies in meteorites have shown that the solar nebula was not completely homogenized prior to the formation of the planetary system (Clayton 1978).); in fact it is believed that beyond the orbits of Mercury or Venus complete vaporization did not occur (Lewis, personal communication). In this case interstellar grains could have served as condensation nuclei for the nebular gasses in the outer solar system. Comets would then form as accretion products of these grains, composed of presolar material and nebular condensates.

In this case there should indeed be a close similarity between the refractory cores of cometary grains and the small refractory interstellar grains. In additon to similar silicate features, two other analogies are apparent: 1) The two component nature of the cometary material is analogous to the two types of grains found in circumstellarshells: absorbing grains around carbon rich stars, and silicate grains around oxygen rich stars. 2) The size distribution of the dust in all comets studied is very similar among the comets and shows some similarities with the interstellar dust.

The homogeneity among the observed dust size distributions in comets seems to be an indication of similarities in their nuclei and not an artifact of the submlimation process that carries the dust into the coma. Brin and Mendis (1979) have shown that at 1 AU the subliming ices in a comet like Halley will carry away particles as large as several cm; however, the size distribution of the dust in 3 bright comets, observed within 1 AU, showed a negligible number of particles larger than 0.025 cm in radius (Delsemme 1982), indicating that it was not the sublimation process which limited the maximum size of the particles ejected. Attempts to observe continuum emission at millimeter wavelengths from comets which had not had recent outbursts have yielded negative results, suggesting a lack of particles with sizes equal to or larger than this wavelength. Particles larger than a cm could indeed accumulate and form layers or large clumps of material which would be expelled only during periods of increased activity like outbursts. Such a phenomenon seems to have been responsible for the continuum emission from large grains ($r > 1$ cm) observed at radio wavelengths by Brandt (personal communication). These large clumps may also give rise to fireballs observed by the prairie network associated with cometary orbits (Wetherill and Revelle 1982). There is not enough information to determine what fraction of of the total mass of solids ejected by comets is in the form of these clumps; however, the fireballs associated with them indicate a very friable consistency, suggesting that they are loose aggregates of the smaller particles observed in the coma.

As mentioned above the size distribution of cometary grains is not exactly equal to that of interstellar dust. Comet dust ranges between 0.3 μm to about 10 μm for all comets observed in the infrared with a distribution peaking around several microns. Interstellar dust however seems to peak in the submicron range, although there is not much information to constrain the upper limit. So if the cometary grains have in fact an interstellar origin, they have accreted into larger grains.

Now if comets are as primitive as we suspect, one would expect there to have been little processing of the presolar grains and maybe some identity of them to be retained. An example of this may be the Brownlee particles, interplanetary particles collected in the upper atmosphere, and at least some of which are believed to have a cometary origin. The majority of these particles are on the order of 1 μm in size, some are single crystals, and others are aggregates of smaller grains ranging in size down to about 0.1 μm (Brownlee 1978). These amorphous submillimeter grains could be the interstellar particles which, welded together, formed the majority of the refractory cometary grains which in turn, as the nebula cooled, acquired icy mantles. The composition of most of these grains is varied, but not diagnostic of either solar or interstellar origin. It would be interesting, however, to compare their size distribution and structure to that of condensates from the outer nebula, unfortunately we have neither enough constraints to make any meaningful theoretical predictions nor access to any sample of such material; Maloney (1980) concludes that CI chondrites have undergone too much processing to retain any size information of the original grains. As a final comment on Brownlee particles, and since interstellar grains seem to be amorphous, one could speculate that the well developed crystals in his sample are of solar system origin, either condensates, or more likely of asteroidal origin.

Origin of "Gassy" and "Dusty" Comets

There is considerable observational evidence for the undifferentiated nature of cometary nuclei and for the uniformity of their volatile composition. Why, then, do they exhibit such a wide range of dust to gas ratio. Donn (1977) concludes that this ratio is independent of the age of the comet and that there are about as many "dusty", "intermediate" and "gassy" comets among short period, long period, and nonperiodic comets. If the variation is not an evolutionary or differentiation effect, it has to be the result of inhomogeneities in the formation site.

If comets did indeed form in the region of the outer planets, one can hypothesize that they would be formed with a range of dust to volatiles ratio produced by volatile enrichment. The fact that the dustiest comet observed so far has been Comet West, with an H_2O/solids ratio of 1.6 at 1 AU, and that the expected equilibrium ratio for the nebula is around 2 (Delsemme 1977) is indicative of volatile enrichment and not dust enrichment or volatile depletion.

Volatile enrichment has happened elsewhere in the nebula, and is cited as evidence for episodic condensation in several distinct zones of the early solar nebula found by Boynton (1978). He finds that in one of the Ca-Al-rich aggregates in the Allende meteorite the rare earth pattern is very strongly fractionated by loss of the least volatile rare earths, indicating that they condensed from a gas that was previously fractionated by the condensation and removal of a more refractory phase. This phenomenon ocurred at a much higher temperature regime than that of the formation site of comets, and I do not claim that volatile enrichment in comets was produced by the same process that produced it in these Allende aggregates, however, it has been observed to occur in the early solar nebula and could very well have occurred in comets.

In order for comets to be observed today, they have to have been, after formation, in an area of the solar system cold enough to maintain their high volatile content; they also have to be in an area where frequent small perturbations will send them into the inner solar system. These two conditions define the Oort cloud as the only area from which we should expect comets to come. If they were in the inner solar system, they would not survive the high temperatures for more than 10^4 or 10^5 years; if they were within the orbit of Pluto, planetary perturbations would make their orbits unstable; and if there are some just beyond the planets (a few hundred AU), we cannot see them and they are still too far from the nearest stars for their gravitational perturbations to send them into the inner solar system. Therefore the gassy and dusty comets which originally formed in regions of the nebula near the giant planets were perturbed out and many were ejected from the solar system; about 10% of the original population (Fernandez 1982, Weissman 1982) were not ejected but their aphelia were so large that the influence of nearby stars randomized their orbits. The final product is what we now know as the Oort cloud, a spherical shell of comets orbiting around 4-6 x 10^4 AU from the sun.

REFERENCES

A'Hearn, M. F., and Millis, R. L. (1980). Astron. J. 85, 1528 (see Erratum 86, 802).

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

A'Hearn, M. F. (1982). Astronomy Program, University of Maryland, comet specialist.

Becklin, E. E., and Westphal, J. A. (1966). Astrophys. J. 145, 445.

Becklin, E. E., Neugebauer, G., and Werner, M. W. (1974). Icarus 23, 561.

Belton, M. J. S., and Butcher, H. (1982). Nature 298, 249.

Biermann, L., and Michel, K. W. (1978). Moon and Planets 18, 447.

Boynton, W. F. (1978). In *Protostars and Planets*, ed. T. Gehrels (Univ. of Arizona Press), 427.

Brandt, J. C., (1982). NASA/Goddard Space Flight Center, comet specialist.

Brin, G. D., (1980). Astrophys. J. 229, 402.

Brin, G. D., and Mendis, D. A. (1979). Astrophys. J. 229, 402.

Brownlee, D. E. (1978). In *Cosmic Dust*, ed. J. A. M. McDonnell (John Wiley), 295.

Cameron, A. G. W. (1973). Icarus 18, 407.

Campins, H., Gradie, J., Lebofsky, M., and Rieke, G. H. (1981). In *Modern Observational Techniques for Comets*, (Jet Propulsion Laboratory) .

Campins, H., Rieke, G. H., and Lebofsky, M. J. (1982a). Submitted to Icarus.

Campins, H., Rieke, G. H., and Lebofsky, M. J. (1982b). Submitted to Nature.

Campins, H., Rieke, G. H., Lebofsky, M. J., and Lebofsky, L. A. (1982). Astron. J., in press.

Campins, H., and Hanner, M. S. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 341.

Clark, R.N. (1982). Submitted to Icarus.

Clayton, R. W. (1978). Ann. Rev. Nucl. Part. Sci. 28, 501.

Corvisier, J., Despois, D., Gerard, E., Irvine, W. M., Kazes, I., Robinson, S. E., and Schoerb, F. P. (1981). Astron. Astrophys. 92, 195.

Delsemme, A. H. (1966). In Nature et Origine des Cometes, Mem. Roy. Roy. Sci. Leige, 5th ser. 12, 77.

Delsemme, A. H. (1975). In Comet Kohoutek, ed. G. A. Gary, (Washington, NASA-SP 355), 195.

Delsemme, A. H. (1976). Mem. Soc. Roy. Sci. Leige, 6th ser. 9, 135.

Delsemme, A. H. (1977). In Comets, Asteroid, and Meteorites, ed. A. H. Delsemme (Univ. of Toledo Press), 3.

Delsemme, A. H. (1981). In Comets and the Origin of Life, ed. C. Ponnamperuma (D. Reidel), 141.

Delsemme, A. H. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 85.

Delsemme, A. H., and Swings, P. (1952). Ann. d'Astrophys. 15, 1.

Delsemme, A. H., and Rudd, D. A. (1973). Astron. Astrophys. 28, 1.

Donn, B. (1976). In The Study of Comets Part 2, eds. B. Donn, M. Mumma, W. Jackson, M. A'Hearn, and R. Harrington (NASA SP-373), 611.

Donn, B. (1977). In Comets, Asteroids, and Meteorites, ed. A.H. Delsemme, (Univ. of Toledo Press), 15.

Donn, B., and Rahe, J. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 203.

Feldman, P. D.(1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 461.

Feldman, P. D., A'Hearn, M. F., and Millis, R. L. (1982). IAU Circ. 3699.

Fernandez, J. A. (1982). submitted to Astron. J.

Fernandez, J. A., and Jockers, K. (1982). Reports on progress in Physics (in press).

Fink, U., and Sill, G. T. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 164.

Finson, M. L., and Probstein, R. F. (1968a). Astrophys. J. 154, 327.

Finson, M. L., and Probstein, R. F. (1968b). Astrophys. J. 154, 353.

Fraundorf, P., Brownlee, D. E., and Walker, R. M. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 383.

Friedmann, C., Gurtler, J., and Dorschner, J. (1979). Astrophys. and Space Sci. 60, 297.

Gatley, I., Becklin, E. E., Neugebauer, G., and Werner, M. W. (1974). Icarus 23, 561.

Greenberg, J. M. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 131.

Hackwell, J. A. (1971). Observatory 91, 33.

Hanner, M. S. (1980). In Solid Particles in the Solar System, eds. I. Halliday and B. McIntosh (D. Reidel), 223.

Hanner, M. S. (1981). Icarus 47, 342.

Hanner, M.S., Veeder, G.J., and Matson, D. L. (1981). Bull. Amer. Astron. Soc., 3, 705.

Hardorp, J. (1982). Astron. and Astrophys. (in press).

Herzberg, G., and Lew, L. (1974). Astron. Astrophys. 31, 123.

Huffman, D. R., and Stapp, J. L. (1973). In Interstellar dust and related topics, eds. J. M. Greenberg and H. van de Hulst, 297.

Huffman, D. R. (1977). Advances in Phys. 26, 129.

Jackson, W. M., Clark, T. and Donn, B. (1976). In the study of comets, eds. B. Donn, M. Mumma, W. Jackson, M. A'Hearn, and R. Harrington (NASA SP-393) 272.

Jewitt, D. C., and Danielson, G. (1982). MPC No. 3737.

Jewitt, D. C., Soifer, B. T., Neugebauer, G., Danielson, G. E. and Matthews, D., (1982). submitted to Icarus.

Johnson, H. L. (1965). Commun. Lun. Planet. Lab., 3, 73.

Johnson, J. R., Fink, U., and Larson, H. P. (1982). submitted to Icarus.

Johnson, T. V., Matson, D. L., Loer, S., and Veeder, G. J. (1975). Astrophys. J. 197, 527.

Kamoun, P., Campbell, P. B., Ostro, S. J., Pettengill, G. H., and Shapiro, I. I. (1982). Science, in press.

Keller, H. U., and Thomas, G. E. (1975). Astron. Astrophys. 39, 7.

Kratschmer, W., and Huffman, D. R. (1979). Astrophys. Space Sci. 61, 195.

Kresak, L. (1979). In Asteroids, ed. T. Gehrels (Univ. of Arizona Press), 289.

Kresak, L. (1981). Bull. Astron. Inst. Czech. 32, 19.

Labs, D., and Neckel, H. (1970). Solar Phys. 15, 79.

Larson, H. P., Feierberg, M. A., Fink, U., and Smith, H. A. (1979). Icarus, 39, 257.

Larson, S. (1982). University of Arizona, Lunar and Planetary Laboratory, comet specialist.

Lebofsky, L. A. (1975). Icarus 25, 205.

Lebofsky, L. A., Feierberg, M. A., Tokunaga, A. T., Larson, H. P., and Johnson, J. R. (1981), Icarus 45, 453.

Lebofsky, L. A. (1982). University of Arizona, Lunar and Planetary Laboratory, comet specialist.

Lebofsky, M., and Rieke, G. H. (1979). Astrophys. J. 229, 111.

Lee, T., and Papanastassiou, D. A. (1974). Geophys. Res. Lett. 1, 225.

Lewis, J. (1982). University of Arizona, Lunar and Planetary Laboratory, Solar System expert.

Low, F. J. (1973). Groundbased infrared measurements. AFCRL-TR-73-0371.

Low, F. J., and Rieke, G.H. (1974). In Methods of Experimental Physics, ed. N. Carleton (Academic Press), 12, Pt. A, 415.

Maas, R. W., Ney, E. P., and Woolf, N. F. (1970). Astrophys. J. 160, L101.

Maloney, P. (1980). Senior Thesis, Geology Department, Harvard University.

Marsden, B. G., Sekanina, Z., and Yeomans, D. K. (1973). Astron. J. 78, 211.

Mendis, D. A. (1978). Moon and Planets 18, 77.

Mendis, D. A., and Brin, G. D. (1977). Moon and Planets 17, 359.

Mendis, D. A., and Brin, G. D. (1978). Moon and Planets 18, 77.

Merrill, K. M. (1974). Icarus 23, 566.

Ney, E. P. (1974a). Icarus 23, 551.

Ney, E. P. (1974b). Astrophys. J. 189, L141.

Ney, E. P. (1977). Science 195, 541.

Ney, E. P. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 323.

Ney, E. P., and Merrill, K. M. (1976). Science 194, 1051.

O'Dell, C. R. (1971). Astrophys. J. 166, 675.

Oishi, M., Kawara, K.., Koybayashi, Y., Maihara, T., Noguchi, K., Okuda, H., and Suto, S. (1978). Publ. Astron. Soc. Japan 30, 149.

Pittich, E. M. (1971). Bull. Astron. Inst. Czech. 27, 143.

Potter, A. E., Morgan, T., Ulrich, B., and Barnes, T. (1974). IAU Colloq. 25. The Study of Comets, NASA SP-393-213.

Probstein, R. F. (1968). In Problems of Hydrodynamics and Continuum Mechanics (Soc. Industr. Appl. Math.), 568.

Rieke, G. H. (1977). Infrared and Submillimeter Astronomy, ed. G. G. Fazio.

Rieke, G. H., and Lee, T. A. (1974). Nature 248, 737.

Rieke, G. H., Low, F. J., Lee, T. A., and Wisneiwski, W. (1975). In Comet Kohoutek Workshop, ed. G. A. Gary (NASA SP-355), 175.

Sekanina, Z. (1974). Sky and Telescope 47, 374.

Sekanina, Z. (1975). Icarus 25, 218.

Sekanina, Z. (1976). In The Study of Comets, ed. B. Donn et al, (NASA SP-393), 893.

Sekanina, Z. (1981). Astron. J. 187, 161.

Sekanina, Z. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 251.

Sekanina, Z., and Miller, F. D. (1973). Science 179, 565.

Sekanina, Z., and Schuster, H. E. (1978a). Astron. Astrophys. 65, 29.

Sekanina, Z., and Schuster, H. E. (1978b). Astron. Astrophys. 68, 429.

Shoemaker, E. M., Williams, J. G., Helin, E. F., and Wolfe, R. F., (1979). in Asteroids, ed. T. Gehrels (Univ. of Arizona Press), 253.

Sill, G. T., and Wilkening L. L. (1978). Icarus 33, 13.

Spinrad, H. (1982). submitted to Publ. Astron. Soc. Pacific.

Stefanik, R. P. (1966). Mem. Soc. Roy. Sci. Leige, 5th ser. 12, 29.

Tomakso, M. (198). University of Arizona, Lunar and Planetary Laboratory, .

Van de Hulst, H. C. (1957). Light Scattering by Small Particles (Wiley).

Veeder, G. J., and Hanner, M. S. (1981). Icarus 47, 381.

Weissman, P. R. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 637.

Wetherill, G. W., and Revelle, D. O. (1982). IAU Colloq. 61, Comets, ed. L. L. Wilkening, 297.

Whipple, F. L. (1950). Astrophys. J. 111, 375.

Whipple, F. L. (1951). Astrophys. J. 113, 464.

Whipple, F. L. (1964). Proc. Nat. Acad. Sci. 51, 711.

Whipple, F. L. (1977). In Comets, Asteroids, Meteorites, ed. A. H. Delsemme (Univ. of Toledo Press), 25.

Zaikowski, A., and Knacke, R. F. (1975). Astrophys. and Space Sci. 37, 3.

Zeilik, M., and Wright, E. L. (1974). Icarus 23, 577.