Cometary Dust

Tadashi Mukai

Department of Earth Sciences, Kobe University, Kobe 657, Japan

1. Introduction

The exploration of Comet Halley in 1985-86 has revealed various important aspects of cometary materials. For example, it was found that the cometary nucleus is an irregular shape with a rough surface consisting of black materials. Furthermore, there exists “craters” and “mountains” on its surface, and the ejection of gas/dust occurs from limited areas on the surface of the cometary nucleus (about 10% of the total surface areas) (e.g., Keller et al., 1987). A large amount of small grains with radii less than 0.1μm, which are not seen from the ground-based observations, has also been detected by in situ measurements (e.g., McDonnell et al., 1987).

In this article, we will focus our interest on the post-Halley knowledge on cometary dust and review what we have learned about cometary dust in a few years.

2. Chemical properties of cometary dust

Our pre-Halley knowledge on the chemical properties of cometary dust was very limited. A reasonable expectation of the presence of silicate-like minerals among the cometary particles has been deduced from the 10μm-emission peak observed in many comets. In addition, a featureless curve of the energy spectrum in the middle infrared wavelengths was speculated by the thermal emission from the “black-body”-like materials in the cometary dust (see, e.g., Ney (1982)).
Careful analyses of the data obtained by the *in situ* time-of-flight impact-ionization mass spectrometers on board Giotto, Vega-1 and Vega-2 spacecrafts have provided new and valuable information of chemical components of cometary grains. That is, Halley's dust is composed of two end member
compositions, *i.e.*, CHON and SILICATE (Jessberger and Kissel, 1991), where the "CHON" means the particles formed from the light elements of H, C, O, and N. It is reported that the mineral grains are heavier than the organic ones and are seen closer to the nucleus (Clark *et al.*, 1987; Hsiung and Kissel, 1987). None of the detected particles are single mineral grains (Jessberger *et al.*, 1988; Lawler *et al.*, 1989). These facts may suggest a fragmentation of some large mineral grains after ejection from the nucleus and a production of small organic debris in the cometary atmosphere, as will be discussed later.

Furthermore, Lawler *et al.* (1989) have shown that most Mg appears to be contained in silicates whereas Fe is contained in a range of materials such as metal, magnetite, sulfides, and silicates (see Fig. 1). It is expected that during cooling of a solar gas, forsterite (olivine) is condensed at typical pressure-temperature (say, $1 \times 10^{-10}$ atm and 1500K, respectively), whereas at that condition the minerals would have only negligible Fe$^{2+}$ contents, *e.g.*, $1 \times 10^{-3}$ mol % at 1500K (Anders, 1986). With falling temperature $T$, the equilibrium Fe$^{2+}$ content rises, reaching finally Fayalitic olivines at $T < 500$K (see Fig. 2). Therefore, Fe$^{2+}$ content in olivines may indicate the

![Diagram](image-url)  
**Fig. 2.** Condensation of olivine particles.
equilibrium temperature in the condensation region of these dust particles. If the above results reported by Lawler et al. (1989) are real, the cometary grains might be condensed at the temperature $\gg 500K$.

From the Fe/(Fe+Mg) histograms and the Fe/Si vs Mg/Si binary diagrams, Lawler et al. (1989) have also shown that the anhydrous particles collected in the stratosphere appear to be the best overall match to Halley's dust particles. It is still unsolved problem, however, when and where anhydrous silicates in cometary dust, if they exist, formed (see, e.g., Anders (1986)).

It is concluded by Jessberger and Kissel (1991) that within a factor of two, the abundances of the rock forming elements are the same as in the whole solar system, but the CHON elements are more abundant than those in CI-chondrites and approach the solar system abundances (see Fig. 3). These evidence strongly suggest that the mineral grains in Halley's dust are

![Diagram](image_url)

Fig. 3. Abundances in C1 chondrites; Halley dust alone and Halley dust plus ice (data cited from Jessberger and Kissel (1991)).
likely pristine, unadulterated material from the early solar system.

3. Isotopic abundances

Isotopic ratios in cometary dust may contain important information about the physical conditions in the environment where these grains were formed. Based on an analysis of spectroscopy of several comets, it is shown that an acceptable range of the stable carbon isotopic ratio deduced from gaseous emission in comets is $70 \sim 120$ (the terrestrial ratio is about 89; e.g., Solc et al., 1987).

The in situ mass spectrometers have made it possible to examine the isotopic abundances of grain particles for O, Mg, S, Cl, and Fe, as well as C. It has been reported that the isotopic abundances for O, Mg, S, Cl, and Fe are near to the terrestrial values (see, e.g., Solc et al. (1987)), but higher (90 ~ 5000) ion intensity ratios 12/13 are real $^{12}$C/$^{13}$C ratios (Fig. 4). This higher values might suggest the existence of interstellar grains in comets or

![Fig. 4. Ion intensity ratios 12/13 deduced from in situ measurements in P/Halley (after Jessberger and Kissel (1991)).](image-url)
result from ion-molecule reactions.

4. Spectral features

From spectral features in infrared spectrum of comets, one can derive the chemical nature of cometary dust.

The 3.4\(\mu\)m emission

The existence of the 3.2-3.4\(\mu\)m feature found in comet Halley by the infrared spectrometer on board Vega spacecraft, IKS, (Combes et al., 1986) was confirmed by ground-based observations (e.g., Knacke et al., 1987). However it is still uncertain whether the 3.4\(\mu\)m emission is by dust or gas (Combes et al., 1988; Knacke, 1989; Colangeli et al., 1989). Encrenaz et al. (1987) have shown in terms of resonance fluorescence that hydrocarbon molecules are emitters. On the other hand, Colangeli et al. (1990) have proposed hydrogenated amorphous carbon (HAC) grains for a carrier of this emission band. This emission feature has been seen in, at least, three comets (see Knacke (1989)); Halley, Wilson (1986\(\ell\))(Allen and Wickramasinghe, 1987), and Bradfield (1987s)(Brooke et al., 1990). Gehrz et al. (1989), however, have reported no evidence of the 3.4\(\mu\)m emission feature in P/Encke.

The 10\(\mu\)m emission

The history of the 10\(\mu\)m emission in comets has begun since 1970 when Maas et al. (1970) demonstrated the presence of the silicate emission feature at a wavelength of nearly 10\(\mu\)m in Comet Bennett (1970 II)(see, e.g., Ney (1982)). In Comet Kohoutek (1973 XII), a medium resolution spectrum obtained by Merrill (1974) showed a featureless excess much like that seen in the circumstellar dust shells. As a result, its broad, structureless feature was interpreted by the thermal emission from the amorphous silicate grains (e.g., Ney, 1982).

A structure in the 10\(\mu\)m emission, i.e., at least, one sharp peak at 11.3\(\mu\)m as well as the usual broad peak at 9.7\(\mu\)m, has been found in Comet Halley at sun-comet distance \(r\) of 1.32 AU before perihelion (Bregman et al., 1987). This peak structure has been confirmed in Comet Halley at \(r = 0.79\) AU before perihelion (see Fig. 5), \(r = 0.67\) AU before perihelion (Bouchet
et al., 1987) and \( r = 0.79 \) AU after perihelion by IKS on Vega spacecraft (Combes et al., 1988). Its twin-peaked emission feature was also detected in Comet Bradfield (1987s) at \( r = 1.44 \sim 1.45 \) AU after perihelion (Hanner et al., 1990), in contrast to no feature in Comet Wilson (1986\( \ell \))(Lynch et al., 1989). The carriers of this emission at 11.3\( \mu m \) seem to be crystalline olivine, as noted first by Bregman et al. (1987) based on the transmission
spectra of the collected particles from the stratosphere. Furthermore, since olivine is one kind of anhydrous silicates, this speculation is consistent with the result proposed from analyses of chemical properties of impact dust particles mentioned above.

Mukai and Koike (1990) have investigated the optical constants of olivine particles in the infrared wavelengths based on their laboratory measurements (see Fig. 6). Consequently, assuming the spherical particle of olivine, it has been found that the emission peaks occur for smaller olivine particles with radii $s$ less than a few tenth micrometers at a wavelength of 16.3, 18.6, 23, 28, and 33.6$\mu$m, as well as a twin-peaked structure in the 10$\mu$m region (see Fig. 7). On the other hand, no or somewhat weak peaks appear for larger grains ($s >$ a few $\mu$m). This may suggest that the size distribution of olivine particles is one of key parameters to control the appearance of the twin-peaked structure in the 10$\mu$m emission band. The existence of such high temperature minerals, i.e., crystalline olivine in the cometary dust brings new important questions concerning their origin and evolution in the early solar system, as noted before.

![Fig. 6. Optical constants of olivine particles. In the figure, $n$ is a refractive index and $k$ denotes an absorption coefficient (data from Mukai and Koike (1990)).](image-url)
Fig. 7. Emission efficiency $Q_{\text{abs}}$ for olivine particle with a radius $s$ (Mukai and Kojie, 1990).
5. Size distribution of cometary dust

A size distribution of cometary dust has always been indirectly determined from their visible scattering and thermal emission. Many assumptions are required to estimate the size distribution of cometary dust particles such as the shape of particle and the optical constants of grain materials. A proposed size distribution compiled in the pre-Halley era is shown in Fig. 8 as a dotted curve. Direct access to the size distribution of cometary dust was first developed by the in situ measurements of Comet Halley. Several kinds of impact detectors have provided the data of the dust particle influences along the trajectory of a space probe through the coma of comet. For example, the cumulative flux distribution for DIDSY (Dust Impact Detection SYstem) and PIA (Particulate Impact Analyser) on board Giotto is shown in Fig. 9 (McDonnell et al., 1987). Flux profiles are presented, to a first approximation, as a $R^{-2}$ flux dependence, where $R$ is the distance of the detection point from the cometary nucleus, although significant deviations from this dependence are observed, particularly close to the nucleus.

Extremely small grains (about $1 \times 10^{-16}$g in mass), which are not seen from the ground-based observations (refer to the dotted curve in Fig. 8), have unexpectedly appeared in the size distribution deduced from the impact data (see the solid/dashed-dotted curves in Fig. 8). Recently they have gradually lost their importance because of their ineffective role in scattering.

Fig. 8. Size distribution $n(s)$. In the figure, $s$ means a grain radius, deduced from the in situ measurements (V: Vega model, G: Giotto model), and the pre-Halley reference model (V)(see Mukai et al. (1985)).
of light and thermal emission (Hanner et al., 1987), and in total mass of ejected grains (Gruen et al., 1987). We would like to stress, however, that their role should be examined in more detail in future work, e.g., as the second source of gas in the coma (Lamy and Perrin, 1988), the progenitor of the origin of life (Clark, 1989), and a link between large molecules and dust grains.

On the other hand, 'anomalous' excess of large grains in the mass range 1μm to 1mg plays a key role in a determination of the dust to gas mass ratio ejected from the cometary nucleus (Green et al., 1987). Taking account of the observed mass excess in the coma, the ratio is estimated to be 1.5 (Grün et al., 1987) and 2 (McDonnell et al., 1991). Crifo (1987) has given its ratio 2.5 from a comparison of dust size distribution expected from hydrodynamics of dust in the coma with that from the optical observations. Assuming \((\text{C/Mg})_{\text{dust+gas}} = \text{solar}\), Jessberger and Kissel (1991) has set its ratio to be 2.7.

It has been reported that at least two impacts of large particles (nearly 10mg and 4g) were detected in Suisei (one of two Japanese spacecrafts in Halley's mission) from an analysis of a time-variation of spin axis of the spacecraft (Uesugi, 1986). The existence of large grains (1 ∼ 50mg range) has also been confirmed from the sudden change of a viewing direction of the Halley Multicolour Camera (Curdt and Keller, 1990). These large grains
are ejected from a cometary nucleus with the low relative velocity (Crifo, 1987; Cremonese and Fulle, 1989), and consequently they stay for a fairly long time along the orbit of the parent comet (Mukai et al., 1989). These estimation may suggest that large particles detected by the spacecrafts were released from the parent comet in the past perihelion passages. Relating to this topics, it is interesting to note that Sykes (1988) have found 64 different dust trails consisting of large grains extended both ahead and behind the comet based on a systematic search of IRAS data. A dust trail in P/Tempel 2 has also been reported (Campins et al., 1990).

6. Variations in dust characteristics

As reviewed above, the exploration of Halley’s comet by space probes has brought us many interesting and new information of cometary dust, which we could not see from the ground-based observations alone. However, we have to keep in mind that these data were collected from very limited areas of cometary coma (along the trajectory of spacecraft) and within very short time interval (roughly a few hours). In addition, we have explored only one comet (P/Halley) among several hundreds of the comets appeared in the past. Therefore, the spatial- and time-variations in dust properties, as well as the diversity and similarity of comets should be examined in more detail in future work. We will give a brief review on this topics in the followings.

Spatial variations

The use of two-dimensional detector arrays in comet observations has brought about several new aspects in the study of the dust coma. In Comet Halley, it has been found that the radial brightness gradients in JHK colors were steeper than the 1/d expected for a steady-state isotropic outflow of dust, where d is the projected distance from the nucleus. In addition, the bluest colors were seen at the photocenter (Campins et al., 1989). Furthermore, an increase in albedo away from the nucleus (Hammel et al., 1987), and a maximum polarization in dust jets (Eaton et al., 1988) have been reported. Hoban et al. (1989) obtained two-dimensional color maps of dust coma in comet Halley. The evidence stated above strongly suggests that the changes in dust properties occur while the grains are travelling in the
coma.

The fragmentation of large conglomerates of particles in the coma was proposed by Simpson et al. (1989) from their detection of a rapid increase in dust fluxes within a short time interval (10s). They have called its event "clusters of particles or dust packets" consisting of low mass particles ($\sim 1 \times 10^{-13}$ g). For fragmentation mechanisms in the cometary coma, electrostatic forces on the fluffy-like particles with low tensile strength (Boehnhardt and Fechtig, 1987) and evaporation of 'CHON' grains (Lamy and Perrin, 1988; Wallis et al., 1989) have been proposed, but this is still unsolved problem.

Temporal variations

Temporal variations in dust properties, associated mainly with jets or bursts in comet, have been observed. In Comet Halley, a linear polarization increases during outbursts (Kikuchi et al., 1987) and J-H colors become bluer at a maximum of brightness (Campins and Tokunaga, 1988). One of the possible cause of these phenomena is an enhancement of small grains during the outbursts (Mukai et al., 1987).

Diversity in dust properties

Newburn and Spinrad (1989) have shown a large variation of dust production rate in 18 different comets. The absence of a correlation between the color and the Sun-comet distance has been found in 23 comets by Jewitt and Meach (1988). Both results may suggest the diversity in dust characteristics in different comets. Recently, Kikuchi et al. (1990) have shown that the polarization degrees in comet Austin (1989c1) are significantly smaller in a phase angle (Sun-comet-Earth angle) larger than 30 degrees, compared with those observed in comet Halley, in spite of the agreement of both results in a phase angle less than 30 degrees. This also might cause a difference in dust properties in different comets. Further monitoring of the polarization in other comets is highly required to study the diversity and the similarity of dust characteristics in different comets.

Acknowledgements

This work was supported by the Grant-in-Aid for Scientific Research on Priority Areas (Origin of the Solar System) of Japanese Ministry of Ed-
ucation, Science, and Culture (Nos. 62611007, 63611007, and 01611007).

References


Clark, B.C., 1989, Comets as the most likely progenitor of the origin of life, in Comets in the Post-Halley Era (abstracts), p. 182.


Ney, E.P., 1982, Optical and infrared observations of bright comets in the range 0.5μm to 20μm, in *Comets* (ed. L.L. Wilkening) p. 323.