Interpretation on Deep Impact results: Radial distribution of ejecta and the size distribution of large-sized grains

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Several observations of dust grains ejected from the comet 9P/Tempel 1 by the Deep Impact event strongly suggest that the evaporation and expansion of volatiles occurred and that the vapor accelerated some dust grains. When grains are accelerated by gas, size sorting should occur, that is, larger grains tend to stay closer to the nucleus, while smaller grains is pushed farther away. This means that the light at each distance is emitted from identical-sized grains. Hence, we can estimate the size distribution of grains based on the flux as a function of the distance from the nucleus. A simple evaluation indicates that the size distribution of grains with a size larger than ~ 10 μm is expressed as a power law and the index is ~ -4. This is expected to be an alternative method to estimate the size distribution of grains, though detailed analyses and numerical simulations should be necessary to evaluate the error of this method.

Key words: Jupiter family comets, Deep Impact, ejecta, size distribution, MIR observation, SUBARU telescope.

1. Introduction

The impactor launched from the Deep-Impact (DI) spacecraft collided with the comet 9P/Tempel 1 at 2005/7/4 (UT) (A'Hearn *et al.*, 2005). The large amount of cometary materials was ejected. We conducted mid-infrared (mid-IR) observations before and after its collision using COMICS (the Cooled Mid-IR Camera and Spectrometer), mounted on the Subaru Telescope, and both imaging and spectroscopic measurements were performed with three band-pass filters in the N-band with central wavelengths of 8.8, 10.5, and 12.4 μm (Sugita *et al.*, 2005; Kadono *et al.*, 2007; Ootsubo *et al.*, 2007). The observational data indicate that large-scale dust plume ejected by the impact contained a large mass of $\sim 10^6$ kg of solid dust grains and formed two wings approximately ± 45 degrees from the symmetric center (Sugita *et al.*, 2005). These facts are consistent with the gravity-controlled nature of the DI-induced impact cratering. Also, the image data indicate that there are two regions in the plume. In the outer region, which is far from the nucleus and contains dust grains with higher ejection velocities, the slope of the blackbody continuum is flat and the intensity of 10.5 μm silicate feature is small relative to the continuum, and in the inner region, the slope is steep (the intensity at longer wavelength is large) and the intensity of 10.5 μm is relatively large. We can quanti-

tatively understand this result using a simple dust model (e.g., Ootsubo *et al.*, 2007), and this result and the crater formation mechanism (e.g., Melosh, 1989) indicate that the comet 9P/Tempel 1 has a surface layer with a large fraction of small (sub-micron sized) carbonaceous grains whose thickness is ~ 1 m and a subsurface region consisting of a large fraction of sub-micron sized silicate grains (Kadono *et al.*, 2007).

Spectral analyses using the data at the mid-infrared wavelength do not clearly indicate the size distribution at a size larger than ~ 10 μm because large ejecta grains are not optically active. However, their contribution to the total mass of DI ejecta plume is very large. Thus, estimation of the size distribution of the large ejecta grains is of extremely high importance. Consequently, the method to obtain the size distribution at larger sizes is necessary for precise estimation of ejecta mass. Size distribution of large grains can be estimated by modeling the effect of radiation pressure on the grains based on the images of dust clouds (e.g., Jorda *et al.*, 2007). In this paper, we propose an alternative method to estimate the size distribution at a size larger than ~ 10 μm using the observational results of the DI event, taking advantage of the fact that the ejecta release process from the DI impact was practically instantaneous unlike normal activities.

2. Observational Results

We denote the flux at each wavelength in the N-band as $I_{8.8}$, $I_{10.5}$, and $I_{12.4}$, respectively. For all the results, the flux on July 2 (i.e., two days before the collision) is subtracted
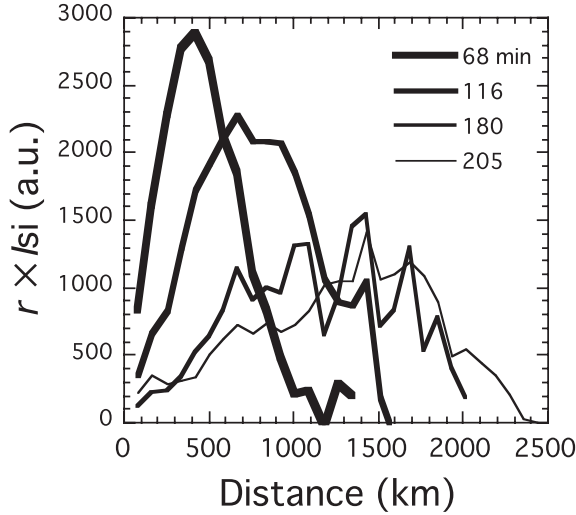
Fig. 1. Radial profiles of $I_{si}(= I_{10.5} - (I_{8.8} + I_{12.4})/2)$ multiplied by r as a function of time at $\sim$1, 2, 3, and 3.5 hours after the impact.

Fig. 3. Radial profiles of $I_{cont} = (I_{8.8} + I_{12.4})/2$ multiplied by r as a function of time.
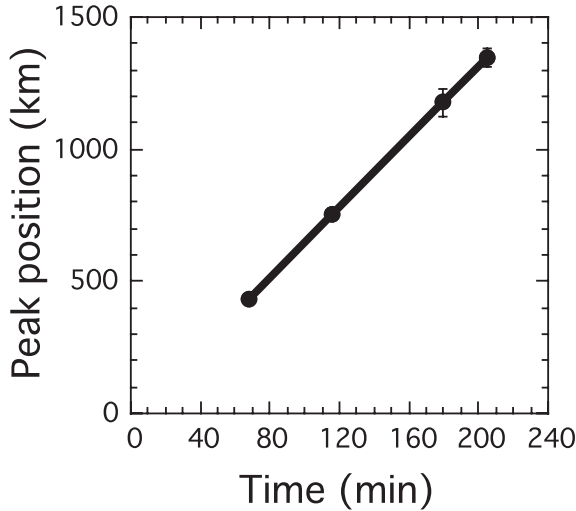

Fig. 2. The positions of the peaks of $r I_{si}$ shown in Fig. 1 as a function of time. It looks that the peaks move outward. Linear fitting indicates that the expansion velocity is 111 m/s.

as a background at each wavelength.

First, we consider I_{si}, which is defined as $I_{10.5} - I_{cont}$, where I_{cont} is $(I_{8.8} + I_{12.4})/2$. This intensity of the 10-μm silicate feature I_{si} indicates the distribution of small silicate grains in the dust plume. In order to investigate the radial profile of spatial dust distributions, radial distance r is multiplied to the flux to reduce the geometrical effect. This $r I_{si}$ is shown in Fig. 1. The distributions at $\sim$1, 2, 3, and 3.5 hours after the impact are shown. There is a peak in each time and that the peak moves outward. We tentatively fit each distribution with a Gaussian and obtain the peak positions. The peak positions r_{peak} are plotted as a function of time (Fig. 2), showing that the peak moves linearly. The linear fit indicates a characteristic velocity of grains of 111.1±0.6 m/s. Thus, we find that the velocity of small silicate grains ($\sim$submicrons) is $\sim$100 m/s.

Next, we consider I_{cont} (Fig. 3). Again, we multiplied r with the light flux I_{cont}. The distributions of $r I_{cont}$ is
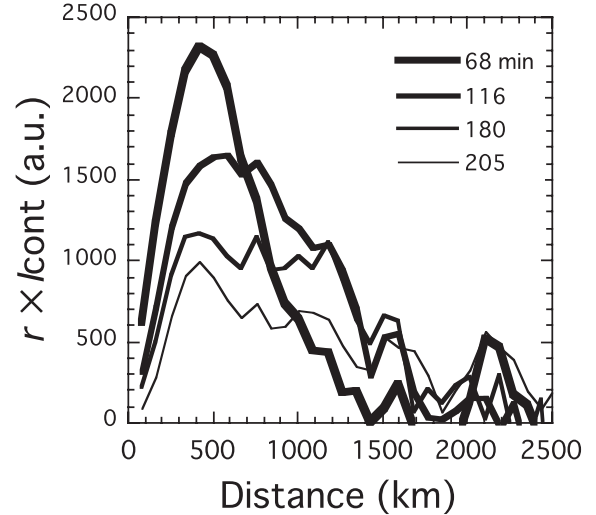
significantly different from $r I_{si}$ in Fig. 1. Although the distribution profile broadens with time, the peak position of $r I_{cont}$ does not exhibit a clear outward motion. Parhaps, a more outstanding change with time is the radial spread of the distribution. The full width half maximum (FWHM) of the distribution of $r I_{cont}$ increases from $\sim$560 km at 1 hour to $\sim$1400 km at 3 hours after the impact. The continuum component I_{cont} is expected to be contributed by not only small grains but also larger ones, whereas the I_{si} component is primarily from small grains within the DI ejecta plume. Hence, the observed difference between $r I_{si}$ and $r I_{cont}$ should reflect the nature of the size distribution of grains. In the next section we estimate the size distribution of grains from the observed flux, I_{cont}.

3. Discussion

A classic ejecta curtain model predicts a monotonically decreasing mass distribution as a function of ejection velocity (e.g., Housen *et al.*, 1983); that is, there should not be such a peak in Fig. 1. This discrepancy has been pointed out (e.g., Sugita *et al.*, 2005) and several authors suggest that an acceleration process for dust grains in the inner portion of the plume may occur caused by volatile evaporation and expansion. Küppers *et al.* (2005) observed a large amount of water vapor, Mg $\sim 4.6 \times 10^6$ kg. They also suggested that this vapor accelerates solid grains. Also, analyses of both radial and angular profiles show that, though the outer part of the dust plume is conical fan-shape (this is consistent with experimental results in laboratories), the inner part is strongly influenced by the dynamics of volatile evaporation and expansion (Sugita *et al.*, 2005).

Here, we consider the dust grains in the inner part of the plume. If the gas drag accelerates the grains ejected by the DI event, the equation of motion of the grains is,

$$\rho_s \frac{\pi}{6} D_p^3 \frac{dv_s}{dt} = C_D \rho_g (v_s - v_g)^2 \frac{\pi D_p^2}{4}, \qquad (1)$$

where ρ_s, v_s, ρ_g, v_g, C_D, and D_p are the density and the velocity of solid grains, the gas density, the gas velocity, the
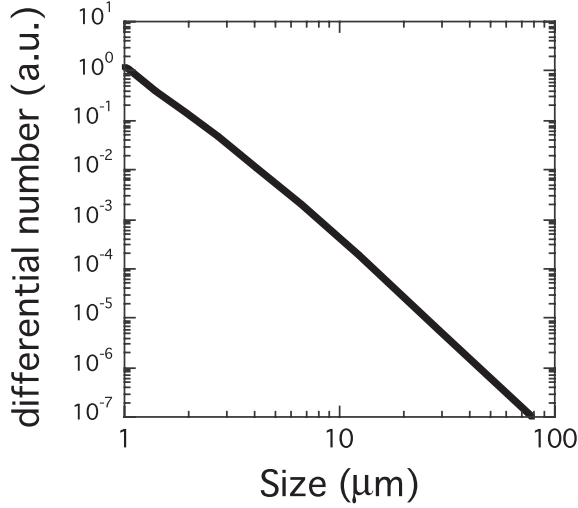
Fig. 4. The differential size distribution of ejected grains estimated from the observed flux. For simplicity, we plot only the case of 2 hours after the impact, but the results from $I_{\text{cont}}(r)$ at the other times are almost the same. At a size larger than $\sim$10 μm, the distribution is expressed by a power-law and the index is $\sim$−4.

drag coefficient, and the size of solid grains, respectively. The dust grains are assumed to be spherical. This equation can be solved as,

$$\frac{3}{2}C_{\text{D}}\frac{\rho_{\text{g}}}{\rho_{\text{s}}}\frac{r}{D_{\text{p}}} = \frac{v_{\text{s}}}{v_{\text{g}} - v_{\text{s}}} + \ln\left(1 - \frac{v_{\text{s}}}{v_{\text{g}}}\right). \quad (2)$$

Here, v_{s} is obtained as a function of r. The terminal velocity v_{sf} of a grain with a size of D_{p} satisfies,

$$\frac{3}{2}C_{\text{D}}\frac{\rho_{\text{g}}}{\rho_{\text{s}}}\frac{r_{\text{a}}}{D_{\text{p}}} = \frac{v_{\text{sf}}}{v_{\text{g}} - v_{\text{sf}}} + \ln\left(1 - \frac{v_{\text{sf}}}{v_{\text{g}}}\right), \quad (3)$$

where r_{a} is the acceleration length. If r_{a} is large enough, v_{sf} should become v_{g}. As shown in Fig. 2, small grains have achieved a constant velocity at our observation time ($\sim$1 hour after the impact), $\sim$100 m/s, which is rather smaller than the sound velocity of H_2O gas at a temperature of 300 K, 430 m/s. That is, the acceleration by gas would terminate at a region nearer the nucleus where we observe. Hence, we assume that r_{a} is rather shorter than the region where we observe (i.e., $r_{\text{a}} < \sim$100 km) and that all grains have achieved terminal velocities when we observe. If we also assume that v_{g} is the sound velocity of H_2O gas at a temperature of 300 K, 430 m/s, ρ_{s}, ρ_{g}, C_{D}, and r_{a} are the same for all grains, and that v_{sf} is 111 m/s when D_{p} is 1 μm (Fig. 2), the relation between D_{p} and the terminal velocity v_{sf} can be obtained from Eq. (3),

$$\left(\frac{D_{\text{p}}}{\mu\text{m}}\right) = 0.049 \left/ \left[\frac{v_{\text{sf}}}{430 - v_{\text{sf}}} + \ln\left(1 - \frac{v_{\text{sf}}}{430}\right)\right]\right. . \quad (4)$$

This equation shows that fast grains are small while slow ones are large. This is consistent with the results obtained by Harker *et al.* (2007) using mid-IR spectra of the impact; they also find that the smaller grains travel faster than the larger grains, in support of Eq. (4).

Since v_{sf} can be written as $v_{\text{sf}} = r/t$ for $r > r_{\text{a}}$, Eq. (4)

becomes a relation between D_{p} and r at a time t,

$$\left(\frac{D_{\text{p}}}{\mu\text{m}}\right) = 0.049 \left/ \left[\frac{r}{430t - r} + \ln\left(1 - \frac{r}{430t}\right)\right]\right. . \quad (5)$$

This equation gives the mean radial position of ejecta grains as a function of time and size.

Observed flux is obtained as a function of r, $I_{\text{cont}}(r)dr$. Using Eq. (5), this can be written as a function D_{p}, $I_{\text{cont}}(D_{\text{p}})(dr/dD_{\text{p}})dD_{\text{p}}$. When the size-number distribution is $n(D_{\text{p}})dD_{\text{p}}$, we assume that the observed flux is proportional to the total cross section of grains, that is, $I_{\text{cont}}(D_{\text{p}})(dr/dD_{\text{p}})dD_{\text{p}} \sim D_{\text{p}}^2 n(D_{\text{p}})dD_{\text{p}}$. This becomes $n(D_{\text{p}}) \sim I_{\text{cont}}(D_{\text{p}})(dr/dD_{\text{p}})/D_{\text{p}}^2$. Thus, $n(D_{\text{p}})$ is obtained as a function of D_{p}. A result is shown in Fig. 4. For simplicity, we plot only the case of 2 hours after the impact, but the results from $I_{\text{cont}}(r)$ at the other times are almost the same. The obtained distribution for grains larger than $\sim$10 μm is fit well by a power-law, $n(D_{\text{p}}) \sim D_{\text{p}}^{-\alpha}$ and the index α is $\sim$4, which is slightly larger than the values provided by fitting the observed spectrum with a power-law in the large grain size range (from <1 to $\sim$10 μm across), an exponent of between −3.5 and −3.6 (Sugita *et al.*, 2005; Ootsubo *et al.*, 2007) and −3.7 (Harker *et al.*, 2007).

4. Summary

We propose an alternative method to estimate the size distribution at a size larger than $\sim$10 μm based on the observational data of the DI ejecta in both time and space. We consider the radial distributions of I_{si} and I_{cont} at P.A. 225. The distribution of I_{si} has a peak which moves $\sim$100 m/s. Assuming that the evaporation of volatiles occurs and that the expansion of the vapor accelerates solid dust grains, we obtain an analytical relation between D_{p} and r. Based on this relation and the observational result of I_{cont}, the size-number distribution of larger grains is estimated. The result indicates that the distribution is expressed as a power law with an exponent $\sim$−4.

Because the contribution of the large grains to the total ejecta mass has been highly uncertain and spectral analyses using the data at the mid-infrared wavelength do not clearly indicate the size distribution at a size larger than $\sim$10 μm, such an estimate on their size distribution is of great importance, though detailed analyses and numerical simulations should be necessary to evaluate the error of this method.

Finally, it is noted that the analysis given by Kadono *et al.* (2007) is on the outer part of the ejecta plume, where the effect of gas acceleration is minimal. The present study focuses on the inner part of the ejecta, where the gas acceleration effect can be significant. In this sense, these two studies are complimentary to each other.

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