MID-IR OBSERVATIONS OF DEEP IMPACT REVEAL THE PRIMORDIAL ORIGN OF A SURFACE OF COMET 9P/TEMPEL 1.

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Introduction: Comets are believed to retain information on the early solar system, but aging processes have altered their nuclus surfaces, prohibiting us from obtaining readily such information from the present state of nucleus surfaces [1]. Thus, their present internal structure, especially the near-surface structure, is extremely important to investigate [1]. One of the most important goals of NASA's Deep Impact (DI) mission was to look inside the comet to resolve this issue. Although a variety of new findings were made by the DI observations, the near-surface structure of the nucleus has not been discussed extensively yet. In this study, we focus on understanding the nature of the comet surface structure using high-resolution mid-infrared (IR) imaging data by the Subaru telescope with three band-pass filters in the N-band with central wavelengths of 8.8, 10.5, and 12.4 mm obtained before and after the DI collision.

The Principle of Analysis: Observations of the DI event indicate that crater formation was largely controlled by gravity [2,3]. In the gravity regime, higher speed ejecta are ejected from a shallower depth, while slower ejecta are biased toward material from deeper in the target [e.g., 4]. If the nucleus has a surface layer chemically/mineralogical different from the substrate, fast ejecta thrown from near the impact site will be seen to contain only materials from the surface layer. Also, slow ejecta, in turn, contain primarily those from the substrate layer. Thus, the vertical distribution of material in the nucleus is reflected in the distribution of ejection velocity. Then ejection velocity is translated further to the radial distance from the nucleus in the dust plume; ejecta in the outer portion of the plume were ejected at higher velocities than those in the inner portion of the plume. Consequently, the materials in the outer portion of the plume originated from the surface layer, and those in the inner portion originated primarily from the subsurface. This relationship enable us to investigate the internal structure of the comet nucleus using obsrvation of ejecta plume induced by the DI impact [5]

Spatial Hetierogenity in Plume Dust Composition: Figure 1 shows the ratio of silicate emission band around 10 μm to the continuum (i.e., $I_{\text{feature}}/I_{\text{cont}}$). Here, I_{feature} is $I_{10.5} - I_{\text{cont}}$ and I_{cont} is $(I_{8.8}+I_{12.4})/2$, where the intensities of mid-IR light at 8.8, 10.5 and 12.4 μm are denoted as $I_{8.8}$, $I_{10.5}$, and $I_{12.4}$, respectively. Figure 1 shows that there is a large variation in the $I_{\text{feature}}/I_{\text{cont}}$ ratio, which represents the distribution of small silicate grains in the dust plume. This ratio is low near the nucleus and increases outward until it reaches a maximum, and then decreases toward the edge of the plume. This trend implies that the abundance of small silicate grains is high in the inner portion of the plume (i.e., the subsurface of the comet) and is low in the outer portion of the plume (i.e., the surface layer).

Emission Temperature of Carbonaceous Gains: Figure 2 shows the spatial distribution of $I_{8.8}/I_{12.4}$, which represents the slope of the continuum. The $I_{8.8}/I_{12.4}$ ratio is controlled by the temperature and composition of the grains in the plume. The $I_{8.8}/I_{12.4}$ ratio increases with the radial distance from the nucleus to the leading edge of the plume. Annular high $I_{8.8}/I_{12.4}$ regions can be found at ~ 1" (Fig. 2A) and at ~ 2" (Fig. 2B) from the nucleus. The peak positions of $I_{8.8}/I_{12.4}$ are clearly outside the peaks of $I_{\text{feature}}/I_{\text{cont}}$ and are associated with low $I_{\text{feature}}/I_{\text{cont}}$ regions in the outer portions of the plume. High $I_{8.8}/I_{12.4}$ ratios can be produced by either small silicate grains or small carbonaceous grains, but the low $I_{\text{feature}}/I_{\text{cont}}$ ratio preclude the presence of a large quantity of small silicate grains. Thus, it is very likely that the outer portion of the ejecta plume is dominated by small carbonaceous grains. When we assume that the outer portion consists of only carbonaceous grains, we can calculate the mean grain size from the observed $I_{8.8}/I_{12.4}$ ratio using an equilibrium radiation model. The observed high $I_{8.8}/I_{12.4}$ ratio (> 1) requires a radiation temperature >350 K. This temperature is the equilibrium temperature of carbon grains with a radius of ~ 0.5 μm at 1.5 AU. Thus, the surface layer of the comet is likely to contain a dominant fraction of small (< ~ 0.5 μm) carbonaceous grains.

Implications for Cometary Surfaces: There are generally two models for the origin of the current surface crust of Jupiter-family comets. One is that the current carbon-rich surface layer was formed by cosmic ray irradiation when the comet was stored for a long time in the trans-Neptune region. The other is that such an old surface layer has been lost during recent perihelion passages and that a new surface layer has been formed by evaporation process on the surface. It is higly unlikely that the the entire surface is covered with an old crust formed in the trans-Neptune region because a comet loses a large amount of mass during each perihelion passage. However, it is possible parts of such an old crust are still left of the surface.

If a current surface layer was formed by evaporation processs during perihelin passages, volatile vapor would drag small grains into the space and leaves only larger grains on the nucleus surface to form a dust mantle [6]. In contrast, if a surface layer of a comet was made by cosmic ray during its long residence in the trans-Neptunian region, the surface layer would contain a large amound of small carbonaceous grains.

Our observations indicate that a large amount of small (< ~ 0.5 mm) grains exist in the surface layer of 9P/Tempel 1. This is consistent with an old crust model and not consistent with a new crust model. Thus, the surface of 9P/Tempel 1, at least around the DI impact site, is likely to have been formed when the comet was in the trans-Neptune region.

This finding is actually consistent with the large number of craters observed around the impact site [2]. Furthermore, observations of the volatiles in 9P/Tempel 1 indicate that the abundance ratios for highly volatile species in the ejecta are in the range of those found for the dominant group of Oort cloud comets [7]. implying that many short-period comets maintain the components they had upon leaving the trans-Neptunian region at ~ 1 m of depth from the surface even after numerous perihelion passages.

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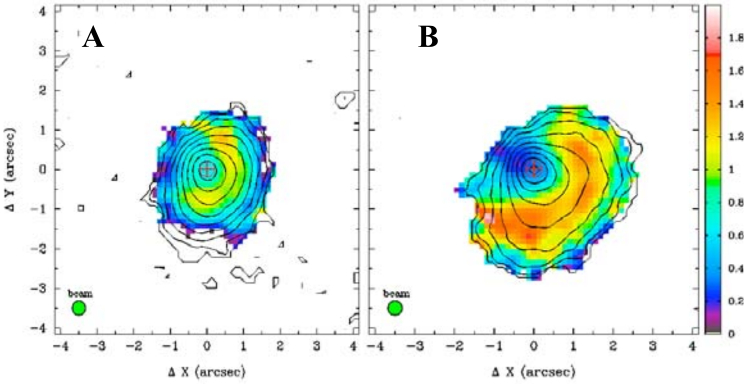

Figure 1. The ratio of emission from small silicate grains to that from carbon grains: $I_{\mathrm{feature}}/I_{\mathrm{cont}}$. (a) 1 hour and (b) 2 hours after the DI collision. The beam size of the full width at half maximum (FWHM) is shown in the lower left in each panel. The contour is log($I_{8.8}$) as a reference for the size of the dust plume induced by the DI impact. The contour levels starts from 2.0 (mJy/pix) with increments of 0.2.

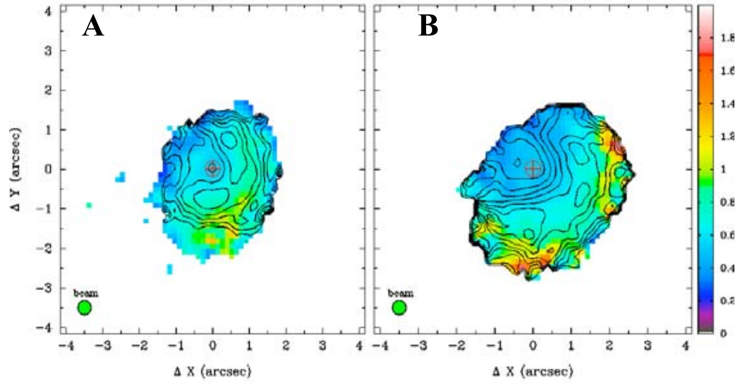

Figure 2. Distribution of the slope of the blackbody continuum: $I_{8.8}/I_{12.4}$. These pseudo color images show the ratio $I_{8.8}/I_{12.4}$. The contours show the $I_{\mathrm{feature}}/I_{\mathrm{cont}}$, which is shown with colar in Fig. 1. (a) 1 hour and (b) 2 hours after the DI impact.