

MID-INFRARED OBSERVATION OF THE DUST PLUME FROM COMET 9P/TEMPEL 1 GENERATED BY THE DEEP IMPACT COLLISION USING SUBARU/COMICS

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ABSTRACT

We carried out mid-infrared observations (multi-band imaging and N-band spectroscopy) of the Deep Impact collision with a Jupiter family comet 9P/Tempel 1 using the Cooled Mid-Infrared Camera and Spectrometer (COMICS) on the 8.2 m Subaru Telescope. Imaging observations reveal that a large fan-shaped impact ejecta was extended to the south-west direction from the nucleus, which is close to the surface normal vector of the impact point of the comet. The N-band spectrum (8–13 μm ; $R \sim 250$) of the dust ejecta from the comet nucleus 3.5 hours after the Deep Impact event shows a strong crystalline olivine feature. We also made spectroscopic observations 24 hours before and 28 hours after the impact. These spectra have no evident silicate feature in the 10 μm region. We present several spectra at the different positions from the comet nucleus, and report the preliminary result of our fitting analysis using a thermal emission model of cometary dust grains. The mass ratio of crystalline to amorphous silicate grains for the dust ejected from the subsurface of 9P/Tempel 1 is much larger than the dust in the coma of other Jupiter family comet, such as 78P/Gehrels 2, but similar to Oort cloud comets, such as Hale-Bopp.

1. INTRODUCTION

NASA's Deep Impact (DI) mission generated a hypervelocity collision between its 370 kg copper-based projec-

tile and comet 9P/Tempel 1 on July 4, 2005 UT [1]. This collision successfully excavated fresh cometary material (gas, ice and dust) underneath a presumable refractory crust on the surface. Observations of such fresh and pristine materials are highly valuable for studying comets and the origin of the Solar System. Comets are believed to be the most pristine remnants from the early solar nebula era of dust grain evolution and planetary formation. They are generally divided into two major dynamical groups; long-period Oort cloud comets (OCs) and short-period Jupiter family comets (JFCs). OCs are thought to have been born in and ejected from the Jupiter-Uranus region, whereas JFCs originated in the trans-Neptunian region [2, 3]. The information on the dust grain properties, such as grain size and mineralogical composition, of these two groups which have different origins provides insight into the thermal processing and radial transport of dust in the early solar nebula [4]. Thus spectroscopic observations of ejecta dust from the subsurface of a JFC nucleus, as well as impact physics, are expected to be extremely important.

Since equilibrium thermal radiation from the comet has its peak around 10 μm and silicate grains have a number of key diagnostic spectral features in mid-infrared (mid-IR) region, spectroscopic observation in the mid-IR wavelength region is highly valuable. However, the spectral coverage of the infrared spectrometer on the DI spacecraft is limited to the range between 1.05 and 4.8 μm [1]. Based on this point of view, we carried out mid-IR observations (multi-band imaging and N-band spectroscopy) from the ground on Mauna Kea. Main results of our imaging observations about the cratering process

by the DI impact are already reported in [5, 6]. We will mainly show the results of spectroscopic observations in this article. The Gemini/MICHELLE team also conducted the mid-IR spectroscopic observations at Mauna Kea and derived grain properties of comet 9P/Tempel 1 [7].

2. OBSERVATION

The DI event was observed with the Cooled Mid-Infrared Camera and Spectrometer (COMICS), which is mounted on the 8.2 m Subaru Telescope on Mauna Kea [8, 9, 10]. Imaging observations (N-, Q-band) of the pre- (1 and 2 days before) and post- (1–3.5 hours and 1 day after) impact were done from July 2 to 5 (UT) in the 8.8, 10.5, 12.4, 17.7, 18.8, 20.5 and 24.5 μm bands [6]. The main objective of this observation is to measure accurately the time evolution of the mid-IR luminosity and SED of comet 9P/Tempel 1, and to estimate the mass of the ejecta from the nucleus induced by the DI collision [6]. In addition to the ejecta mass estimation, we also expected to examine the mineral composition of pristine materials within the subsurface layers underneath the highly processed nuclear surface of the JFC with the spectroscopic data. Three N-band low-resolution spectroscopic observations (8–13 μm ; $R \sim 250$) were also made 24 hours before, 3.5 hours after, and 28 hours after the DI impact event. The on-source integration time for spectroscopy of each day is 406.8 sec, 271.2 sec, and 226 sec, respectively. We selected κ Vir (HD 124294) as the calibration star for the spectroscopy [11]. Standard reduction procedures same as our previous comet observations were applied for aperture photometry and spectroscopic data. Detailed descriptions about the reduction procedures are given in [12, 13].

3. RESULTS

3.1. Multi-band imaging in N-, Q-band

Subaru/COMICS successfully captured the rapidly changing phenomenon occurring around comet 9P/Tempel 1 after the impact. The impact ejecta, as detected by the imaging observations, was fan-shaped and extended to a size larger than 2 arcseconds (1 arcsec corresponds to 648 km on the surface of comet 9P/Tempel 1) in the direction south-west from the nucleus. Information on the style of cratering is very valuable in considering both cometary surface strength and the effective depth of material excavated by the DI impact. These results derived from the multi-band imaging observations together with the spectroscopy are discussed well and summarized in our previous paper [6].

3.2. N-band Spectroscopy

The data of 10- μm spectral feature after the impact also provide further insight into the origin of comets because its spectral shape tells us whether the silicate dust inside the nucleus of a JFC is crystalline or amorphous. The N-band spectrum of 9P/Tempel 1 was taken 3.5 hours after the impact. We also made the spectroscopic observations 24 hours before and 28 hours after the impact. Before the impact the spectrum of comet 9P/Tempel 1 has no evident silicate features in 10- μm region. The spectrum 3.5 hours after the impact exhibits a distinct broad 10- μm silicate feature and a crystalline silicate feature around 11.2 μm can be seen clearly (Fig. 1a). Twenty-eight hours later the silicate feature had faded and the spectrum became similar to that of pre-impact, which has a possible weak excess by relatively large ($\sim 1 \mu\text{m}$) silicate grains (Fig. 1b). Similar results were reported by the Gemini/MICHELLE observation [7].

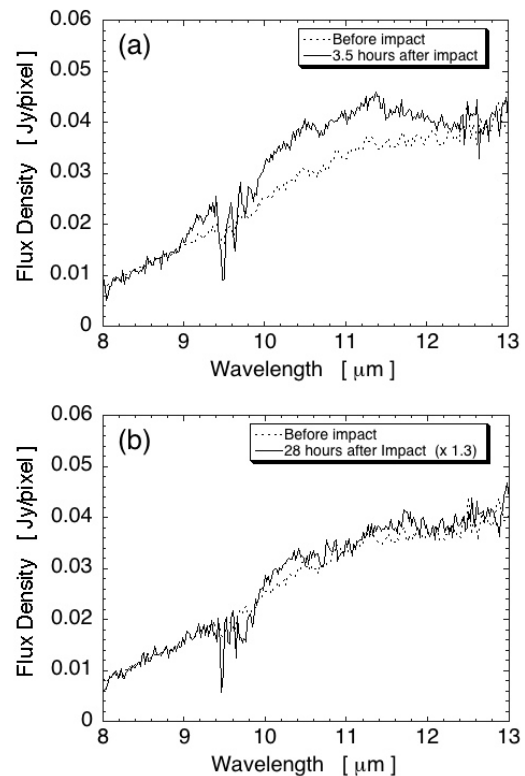


Figure 1. The 10- μm spectra ($0.33'' \times 1.65''$ region including the comet nucleus) of 9P/Tempel 1 (a) 24 hours before and 3.5 hours after the impact, and (b) 24 hours before and 28 hours after the impact. Note that there are still a little uncertainties of absolute flux calibrations between the spectra. There is an effect of telluric ozone absorption in 9.4–9.8 μm region. The spectrum of 28 hours after the impact is 1.3 times scaled in order for the comparison with the data before the impact. 1 pixel = $0.33'' \times 0.165''$ for the slit of this COMICS spectroscopy.

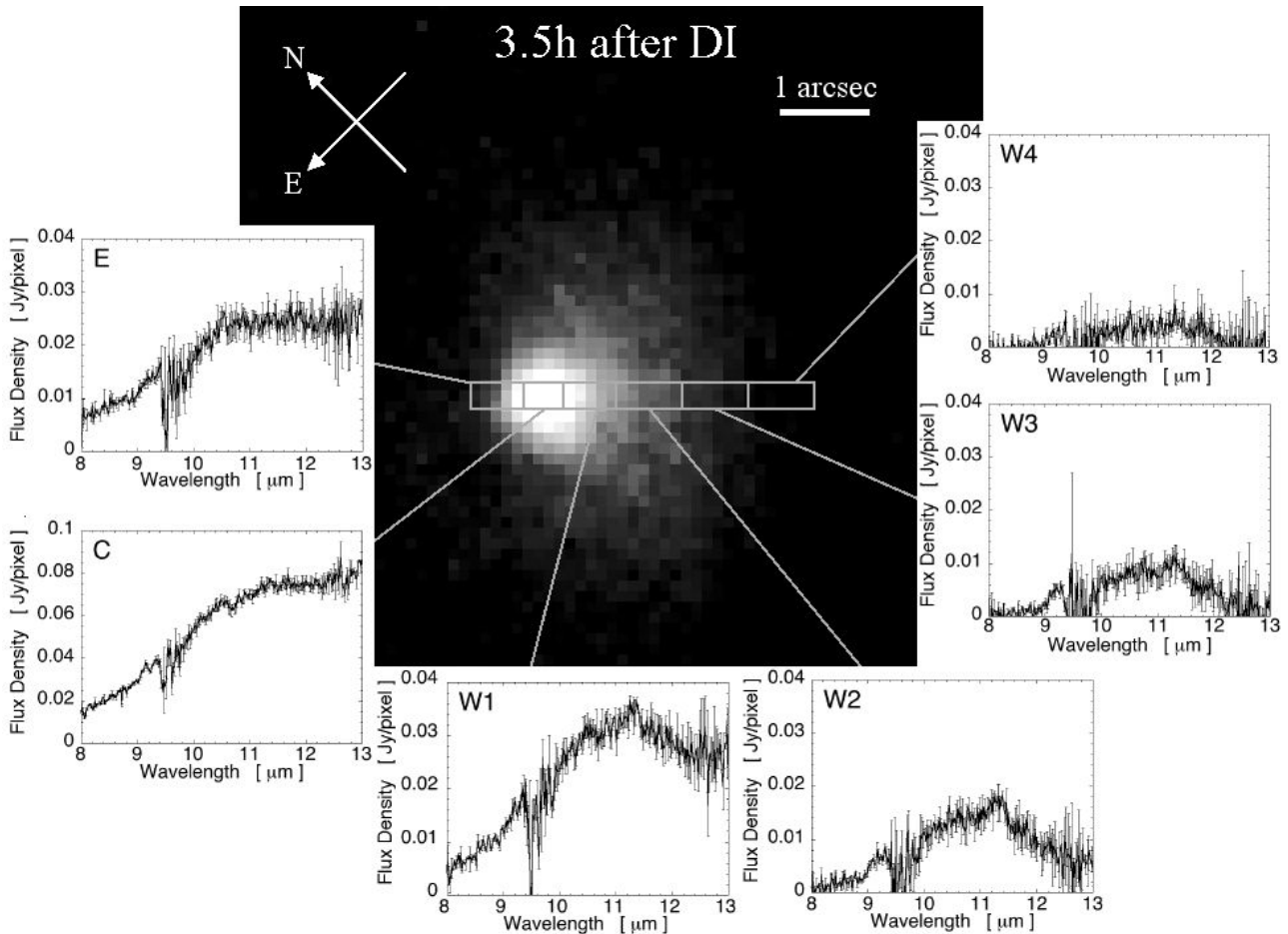


Figure 2. The N-band spectra 3.5 hours after the impact at the six different positions are shown. The DI impactor approached from the south-west side and struck the nucleus. Slit position at 225° position angle is depicted together with the $10.5\text{-}\mu\text{m}$ imaging data of comet 9P/Tempel 1. The on-source integration time is 271.2 sec for spectroscopy and 60.7 sec for imaging. The crystalline silicate feature can be seen in the spectra at the south-west side of the comet nucleus but not at the north-east side.

The N-band spectra 3.5 hours after the impact at six different distances from the comet nucleus (E, C, W1–W4) are shown in Fig.2. We set the slit position along the direction of a symmetry line (at 225° position angle) of the fan-shaped plume from the comet nucleus during the spectroscopic observation. The spectra of the south-west side from the nucleus (W1–W3 in Fig. 2) show the crystalline silicate feature clearly, while it can not be seen in the north-east side spectrum (E). The most distinct crystalline feature can be seen in the W2 spectrum. From this result, the crystalline feature in the spectrum can be attributed to the dust ejected by the DI impact.

In order to derive the spectrum of the ejecta dust itself, we subtract the pre-impact spectrum from the spectrum 3.5 hours after the impact. We use the data at the position W1 hereafter, and the further study on the spectra at other positions will be discussed in our upcoming papers near future. The crystalline silicate feature can still be seen clearly and there seems to be less contribution from amorphous silicate around $9\text{--}10\ \mu\text{m}$ in the resultant spec-

trum, although it has relatively large error-bars. Then, in order to characterize the grain sizes and mineralogical composition (especially the mass ratio of crystalline-to-amorphous silicate, hereafter CAR) of potential pristine grains in the ejecta, we examine this spectrum using a thermal emission model of the cometary dust grains. The method used here is the same as our previous one [13, 14], and similar to the techniques used by previous authors [e.g. 7, 15, 16]. In this thermal emission model, the grain size distribution (Hanner size distribution), porosity (fractal, porous dust grains composed of vacuum inclusions in a matrix are considered as cometary aggregate particles), and five grain components (amorphous olivine and pyroxene, amorphous carbon, and crystalline olivine and pyroxene) are taken into account. The χ^2 fitting for this ejecta dust spectrum has been conducted with the Levenberg-Marquardt minimization.

In Fig.3 the best-fit synthetic spectrum with the observed N-band spectrum of ejecta dust at the position W1 is shown. It is noted that there may be a difference between

the very initial fresh material, which is ejected from near the surface immediately after the DI impact, and the dust observed 3.5 hours after the impact. This spectrum, however, can be considered to represent that of inner dust within the nucleus. The observed spectrum of the 10- μm silicate feature can be reproduced well by the power-law exponent of the Hanner size distribution $N = 3.6$ and the grain radius of the peak position $a_p = 0.4 \mu\text{m}$, and fractal dimension $D = 2.857$. The resulting reduced χ^2 value (χ_v^2) is 1.78. The mass fraction of amorphous pyroxene, amorphous olivine, amorphous carbon, crystalline olivine, and crystalline pyroxene to the total sub- μm (0.1–1.0 μm) grains is 0.05 ± 0.03 , 0.12 ± 0.02 , 0.02 ± 0.01 , 0.73 ± 0.07 , 0.08 ± 0.02 , respectively. As a result we obtain the CAR mass ratio of silicate larger than 4 in sub- μm grains.

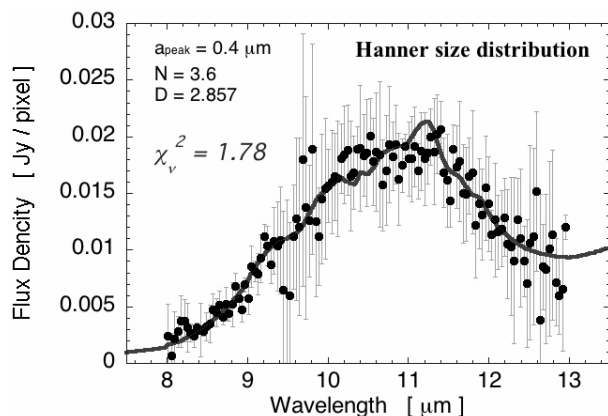


Figure 3. The ejecta dust spectrum (difference between before and after the impact) 3.5 hours after the DI collision at the position W1. The best-fit synthetic model spectrum is shown in the same figure.

4. DISCUSSION

The CAR value of 9P/Tempel 1 derived here is larger than the result by Gemini/MICHELLE [7]. They observed 1 and 1.8 hours after the impact, while we made the spectroscopic observation 3.5 hours after the impact. We used narrower slit (0.33" width) than them and different slit direction along the dust plume for the spectroscopy. From these conditions, it seems that our result shows the characters of subsurface dust grains ejected from the relatively inner nucleus, while Gemini result implies the properties of the initial materials ejected by the DI collision including dust grains near the surface.

With regard to the JFCs, we also observed 78P/Gherels 2 in November 2004 with Subaru/COMICS and succeeded in detection of the crystalline silicate feature [14]. We derived the CAR value using the same thermal emission model used in this paper. The CAR of the ejecta dust of 9P/Tempel 1 has much larger value than the coma dust of 78P/Gehrels 2 (~ 0.86). From the recent observations, it has been found that OCs tend to have the similar CAR

value (~ 2 – 2.5) around 1 AU [13, 16, 17], and the CAR of JFC (78P/Gehrels 2) seems to be significantly smaller than OCs. The sub- μm silicate grains within the subsurface layer below the nucleus of 9P/Tempel have the CAR value slightly higher than that of OCs coma dust [13], and is similar to that of Hale-Bopp at 0.97 AU ($= 3.7$), which is the largest one observed so far [17]. These results imply that JFCs and OCs may have basically the same origin. Recently, it has been suggested that JFCs may not be classical Edgeworth-Kuiper Belt objects, but scattered disk bodies formed in the outer giant planet region [18]. The dust grains in the regular coma of JFCs may be altered by the repeated solar radiation especially during the perihelion passages, and the characteristics of these grains are different from those deep inside the cometary nuclei. To solve this question, it is important to increase the observational samples of JFCs.

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