A Search for Deep Impact’s Large Particle Ejecta

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Summary. The Deep Impact encounter with the nucleus of 9P/Tempel ejected small grains \((a \lesssim 10 \, \mu m)\) into the comet’s coma, evidenced by thermal emission from small dust grains at mid-infrared wavelengths \((\lambda \sim 10 \, \mu m)\) and dynamical simulations of optical images. Meteor-sized particles \((a \gtrsim 100 \, \mu m)\) ejected by the impact will likely have the lowest ejection velocities and will weakly interact with solar radiation pressure. Therefore, large particles may remain near the nucleus for weeks or months after ejection by Deep Impact. We present initial highlights of our Spitzer Space Telescope/MIPS 24 \(\mu m\) camera program to image comet 9P/Tempel at 30, 80, 420, and 560 days after the Deep Impact encounter. The MIPS data, combined with our dynamics model, enable detection of large dust grains potentially ejected by Deep Impact.

1 Introduction

The Deep Impact impactor released an abundance of sub-micron sized particles into the coma of 9P/Tempel. Mid-infrared spectra of the ejecta displayed a strong silicate emission feature, including crystalline silicates, indicating the presence of small particles [3, 13]. Ground-based images of the ejecta showed dust that strongly interacted with radiation pressure, again implying small grains [12]. This small particle ejecta plume was optically thick, apparent from a shadow cast by the ejecta onto the comet nucleus [1]. Though the impact site was available for observation by the Deep Impact flyby spacecraft for 800 s after impact, the crater was wholly obscured by the optically thick ejecta. Had the crater been observed, a size estimate of the crater, and therefore, an estimate of the total ejecta mass, may have been directly determined. Instead, we must estimate the total ejecta mass from observations of the ejecta itself. The gas and small particle dust \((0.1–10 \, \mu m)\) masses have been constrained to be of order \(10^5–10^6 \, kg\) [9, 6, 3, 13], but the mass in larger sized dust grains \((\gtrsim 100 \, \mu m)\) is unknown. If the grains were ejected with typical comet grain...
size distributions \(dn/da \sim a^{-3.5}\), the large dust mass could dominate the total ejected dust mass.

The particle size distribution may have strongly favored small particles; therefore, the surface brightness of large grains would be faint and difficult to detect in contrast with the smaller, more abundant, grains. Schleicher et al. [12], through dynamic modeling of ground-based optical images, estimated that the effective radii of ejected particles ranged from 0.25 to 1.25 \(\mu\)m with ejection velocities of 0.13–0.23 km s\(^{-1}\). Dynamical simulations of larger particles did not agree with the observations, yet this does not preclude their existence since they may be many times less abundant than the small particles. Moreover, there is some evidence for small and large particle segregation in the ejecta [14], likely due to the ejection of larger particles with lower ejection velocities. If the ejected grain size distribution extends beyond 10–100 \(\mu\)m, then for \(v_{ej} < 0.1\) km s\(^{-1}\) the largest particles could remain near the nucleus for days, or even weeks after impact. High sensitivity, long temporal baseline observations, beyond the immediate aftermath of Deep Impact, are necessary to observe any large dust grains generated by crater formation processes. The slowest particles likely remained gravitationally bound to the nucleus and fell back to the surface, therefore, such observations will only provide a lower limit to the total excavated mass. We present dynamical simulations and Spitzer/MIPS images to search for large dust grains in the Deep Impact ejecta.

2 Observations and Models

We initiated an observing program with the Spitzer Space Telescope [16] to observe comet 9P/Tempel with the MIPS 24 \(\mu\)m camera [11] at 30, 80, 420, and 560 days after the Deep Impact encounter. Two observations, obtained on 2005 Jul 31 and on 2005 Sep 23, have been processed and analyzed (see Table 1 and Fig. 1). The images span a 22' \(\times\) 42' area surrounding the nucleus and dust trail. The dust trail is visible in both images as the thin, isolated, linear feature extending from the inner coma to the northwestern edges.

Images of comet 9P/Tempel following the collision with Deep Impact showed a short lived plume of high \(\beta\) particles that quickly dispersed from the vicinity of the comet [10, 6, 12]. Schleicher et al. [12] suggest (based on images 6 days after impact) that very slow moving particles, \(v_{ej} < 0.001\) km s\(^{-1}\), may exist. To predict the location of the large, slow moving, Deep Impact-ejected dust grains in the MIPS images, we will work under the assumption that the high \(\beta\) ejecta plume has a low \(\beta\) component, which was ejected in the same manner, but with lower velocities. The simulations will be created with our Monte-Carlo dynamical model [8].

Schleicher et al. [12] reproduced the ejecta plume using particles with \(\beta \approx 0.24–1.2 (a \approx 0.25–1.25 \mu\)m) and ejection velocities of 0.13 to 0.23 km s\(^{-1}\). Their best model ejected particles in a cone with an opening angle of 70°.
Table 1. Spitzer/MIPS 24 μm post-Deep Impact observations of comet 9P/Tempel.

| Date (UT) | Time ∆T (UT) (days) | Δr_h (AU) | Δs (AU) | Phase Angle (degrees) |
|-----------|----------------------|-----------|---------|-----------------------|
| 2005 Jul 31 04:14 | 26.96 | 1.53 | 0.87 | 40 |
| 2005 Sep 23 21:00 | 81.66 | 1.68 | 1.31 | 38 |
| 2006 Sep 01 08:25 | 424.11 | 3.52 | 3.15 | 17 |
| 2007 Jan 15^c 00:00 | 560 | 4.03 | 3.55 | 13 |

^a^Time elapsed since impact.
^b^Comet-Spitzer distance.
^c^Estimated date of observation.

Fig. 1. Spitzer/MIPS 24 μm images of comet 9P/Tempel. The lowest contour is placed at 3 MJy sr⁻¹, and the contours are spaced at factor of 3 intervals. Celestial N and E, the projected sunward direction (☉), and comet 9P’s projected velocity vector (v) are provided for each image. The comet’s natural dust trail is seen extending from the comet in the negative velocity direction.

and a wall thickness of 30°. The cone was centered at a position angle of 255° and a “phase angle” of 70° (0° is directed toward the Earth, 180° is directly away). We begin modeling Schleicher et al.’s ejection plume with these parameters and verify the parameters by comparison to their images; however, with our model, the ejecta position angle of 225° reported by Sugita et al. [13] produced better agreement with the observations. The simulated images (not shown) exhibit a limb brightened cone at t_{impact} + 0.97 days. The limb brightening persists through each of the time steps. Limb brightening is
not evident in the images of Schleicher et al. [12]. Although optical images from the Hubble Space Telescope (t_{impact} + 1–2 hrs) [2], mid-IR images from the Subaru Telescope (t_{impact} + 3 hrs) [13], and optical images by the Rosetta spacecraft (t_{impact} + 21 hrs) [6] show what may be limb brightening in the ejecta plume. Further modeling and interpretation will be required to resolve this discrepancy.

The evidence for velocity differentiation in the ejected dust is apparent in the optical images of Schleicher et al. [12], the mid-infrared images of Sugita et al. [13], and the mid-infrared spectra of Harker et al. [4, 5]. We posit that there exits a slow moving, large particle component to the ejecta. We modeled the slow moving component with the same cone parameters as the high $\beta$ grains, but with lower $\beta$-values ($\beta \leq 0.1$) and lower ejection velocities ($v_{ej} \leq 0.1$ km s$^{-1}$). The particles are ejected at the time of impact with a uniform distribution of velocities (between 0 and 0.1 km s$^{-1}$) and a logarithmic distribution of grain $\beta$ values ($dn/d\log \beta \propto 1$) ranging from $10^{-4}$ to $10^{-1}$ ($a \approx 6 – 6000 \mu$m). The logarithmic distribution of $\beta$-values ensures all grain size decade bins are equally represented (i.e., there is an equal number of 10 $\mu$m grains as there are 1000 $\mu$m grains). The model simulated the ejection of $10^6$ particles in a 180$^\circ$ cone centered on the derived impact site, as discussed above. Those particles outside of the Schleicher et al. [12] cone were removed from the simulated images.

3 Discussion

Synthetic images of the simulations, given a specific observer geometry, predict the location of large particles that may have been ejected as a result of the Deep Impact collision. We examined the MIPS images from July and September 2005 (Fig. 1) to determine if slow moving, large dust grains are lingering in the vicinity of the comet. Figure 2 presents sub-sections of the two MIPS images and thermal emission contours (isothermal grains) from the large particle simulations, assuming an ejected particle size distribution of $dn/da \propto a^{-3.5}$. The MIPS images have been unsharp masked to enhance the coma asymmetries. In the 2005 July MIPS image, there is a coma feature extending in the anti-solar direction that is coincident with the contours of the simulation. These particles have $\beta$ values ranging from $10^{-3}$ to $10^{-1}$ (lower $\beta$ values are found closer to the nucleus). The 2005 September MIPS image shows the same coma feature (in the anti-solar direction), but the simulated Deep Impact dust has rotated away from the anti-solar direction. We conclude that the anti-solar feature is a young, normal coma feature and not due to Deep Impact liberated dust. The limb brightened cone extending to the lower-right from the nucleus is comprised of high velocity particles with $\beta \lesssim 10^{-3}$ and does not appear to be present in the MIPS images. Possibly, the ambient coma is obscuring the Deep Impact ejected dust. Observations and simulations of comet 9P in September 2006 and January 2007 (when the coma
emission has diminished significantly) will be required to assess the existence of the largest particles ($\beta = 10^{-4} - 10^{-3}$).

Fig. 2. (Left) Spitzer/MIPS images of comet 9P/Tempel enhanced with an unsharp mask to show asymmetries in the comet coma (20' field-of-view). (Right) Contours from our large particle simulations are overlayed on the enhanced MIPS images to show the possible locations of Deep Impact liberated dust at these epochs.

4 Conclusions

The Deep Impact collision with comet 9P/Tempel ejected small particles from the comet nucleus, yet the upper size limit, and therefore total ejected dust mass, is observationally not well constrained. Large slow moving grains ($a \gtrsim 100 \mu m$) in the ejecta plume (if they exist) have yet to be discovered. We simulate observations of large particles ejected by Deep Impact to predict the location of grains in Spitzer/MIPS images of comet 9P/Tempel at 30, 80, 420, and 560 days after the Deep Impact encounter. The larger particles may be observed as an enhancement to comet 9P/Tempel’s trail in MIPS images 420 and 560 days after Deep Impact.
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