The detection, localization, and dynamics of large icy particles surrounding Comet 103P/Hartley 2

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ABSTRACT
The Deep Impact Spacecraft flew past Comet 103P/Hartley 2 on November 4th, 2010. Images revealed the comet to be enveloped in a field of debris composed of fine grained dust, ice, and hundreds of discrete millimeter to decimeter sized particles. In this work, a selection of the brightest particles are identified and photogrammetrically located in 3D space to examine their positions and dynamics. 90% of the particles detected were within 10 km of the nucleus and traveling a few meters per second or slower. The particles exhibit a high degree of temporal variability in brightness, suggesting rotating, heterogeneous and faceted geometries. This style of near-nucleus environment has not been observed in any other comet to date and it may help explain the hyperactive nature of water production on Hartley 2 and similar comets.

1. Introduction
The Deep Impact Spacecraft conducted the DIXI mission’s flyby past Comet 103P/Hartley 2 (H2) on November 4th, 2010 at a minimum distance of 694 km and a relative encounter speed of 12.3 km/s (A’Hearn et al., 2011). During the encounter, the High Resolution (HRI) and Medium Resolution Instruments (MRI) captured images that revealed a field of debris composed of fine grained dust, ice, and hundreds of discrete millimeter to decimeter sized blocks or “particles” (Kelley et al., 2012) enveloping the comet (see Fig. 1). While clouds of large particles have previously been reported in radar data for multiple comets (Harmon et al., 2011; Kelley et al., 2012). This swarming of individual grains in the near-nucleus environment of H2 has not been directly observed in any other comet to date. H2 produces water at a faster rate than should be possible from surface sublimation alone and, as such, is an example of a hyperactive comet (A’Hearn et al., 2011). The comet had been previously reported from ground based observations to have a nucleus with an active fraction >100% (Groussin et al., 2004; Lisse et al., 2009). The “active fraction” of a comet is the surface area required to produce the observed water production rate assuming surface ice sublimation divided by the actual surface area of the nucleus. If the active fraction exceeds the surface area of the comet, it suggests that water gas is produced in the coma or underneath the surface layer. Indeed, a model of the comet’s light curve from the pre-encounter observation campaign indicated a fractional active nucleual area of ~2%, suggesting a significant cloud of icy grains contributed >90% of the total water production rate at perihelion (Meech et al., 2011). The spacecraft observations confirm not only a “halo” of fine icy material but also discrete centimeter-sized particles (A’Hearn et al., 2011; Kelley et al., 2012).

The spatial distribution and behavior of these particles provide insight into their nature and relationship to the comet. In this study, we present an analysis of the identification, localization, and dynamics of particles present in the encounter images taken around closest approach. The goal of this work is to identify and locate the brightest particles surrounding H2 to understand their positions, evaluate their possible motions, and tie dynamics to grain properties. Due to the large number of particles present in each encounter image, our approach to this problem is to robustly calculate the dynamics of a representative group rather than

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The motion of the spacecraft instruments relative to the nucleus (including not only spacecraft flyby velocity but also pointing adjustments) provides a metric to estimate the location and displacement of these particles by stereoscopic reconstruction of particle locations in successive frames. 

Due to the large number of bright spots (or “candidate”) particles, areas that are at least 2 sigma above the background threshold are identified in each image. Images were processed via a high-pass filter to enhance the visibility of the particles. The background is estimated from a box centered on each particle excluding any comet surface, thereby permitting its use as a threshold value. This strategy serves to make the analysis tenable, but does bias the results to the brighter (and thus, probably larger) particles. The brightness of each individual particle is highly variable between images however, with most appearing and disappearing several times during the flyby; details of this phenomenon will be discussed below. Since the particles exhibit a degree of brightness variability throughout the encounter, it is difficult to directly assess correlations between non-constant brightness and velocity or location. The photometric study of these particles as a function of time and relation to velocity and position will be the topic of a future contribution.

3. Technique description

The technique employed here draws on uncalibrated stereo photogrammetry techniques and particle tracking algorithms to establish the geometric properties of each frame and to locate the particles in Euclidian space (e.g., Hartley and Zisserman, 2004). We use the features on the surface of H2 as a “calibration plate in space” to determine camera projection matrices for each image.

For each image frame, we must compute a camera projection matrix—essentially, a mapping from image space ($u, v$) to world or Euclidian space ($x, y, z$, in length units). Since there are only two location variables in image space, a minimum of two different views of the same particle or feature is required to be able to reconstruct its 3D location. In this study, we adopt the direct linear transform (DLT) as our calibration method. The DLT uses the approximation of a pinhole camera (e.g., the collinearity condition) to simplify the mapping from image to world space (e.g., Abdel-Aziz and Karara, 1971; Karara and Abdel-Aziz, 1974; Schairer and Heineck, 2010). The transform is given by:

$$
\begin{align*}
    u &= T_1 x + T_2 y + T_3 z + T_4 \\
    v &= T_5 x + T_6 y + T_7 z + T_8 \\
    &+ T_9 x + T_{10} y + T_{11} z + 1
\end{align*}
$$

(1)

where $u$ and $v$ correspond to the position in image space, $x, y, z$ form the Euclidian position in world space, and $T$ is a $1 \times 11$ transformation vector of coefficients determined during calibration of a known

…images and follow discrete paths during the encounter (see Fig. 1). …

Fig. 1. MRI clear filter encounter image near closest approach of Hartley 2 (left; approximately 800 km from nucleus). Image is stretched to illustrate jets and an icy particle cloud. White box corresponds to the approximate position of the subframes on the right (a-c), which identify and track four example particles over three successive images. Note that the orientation is non-standard; solar direction is from the bottom. This orientation is chosen because it aligns the images horizontally with the spacecraft direction vector; thus all parallactic motion is horizontal for ease of stereo viewing.

attempt completeness; future studies will focus on extending measurements to more particles. Section 2 presents the observations and data. Section 3 explains the methodology of the positional reconstruction. Sections 4 and 5 contain the results and discussion.

2. Data and observations

The DI Spacecraft imaged the nucleus of the comet using both the MRI and HRI CCD cameras (for full description and calibration of these instruments, we direct the reader to Hampton et al. (2005) and Klaasen et al. (2008); details as required for interpretation of the image data will be provided in this manuscript). Bright point-sources, described as “particles” in this work, were detected near the nucleus in the MRI and deconvolved HRI images. These particles, interpreted to be composed primarily of water ice (A’Hearn et al., 2011) were detected at a high density near the nucleus (Kelley et al., 2012). Most particles are consistent with point sources in the MRI camera and are therefore interpreted to be less than 7 m in diameter. Kelley et al. (2012) present a photometric assessment of particle sizes that indicates an upper limit of ~28–340 cm in radius. They are also consistent with point sources in the HRI images. This camera yields an even smaller upper bound on their possible sizes since the HRI camera theoretically has a factor of 5 better resolution than the MRI. Due to a flaw in the pre-launch calibration of the HRI, however, the instrument is out of focus (Klaasen et al., 2008). Deconvolution routines (presented in Lindler et al. (2012)) can restore much of the lost clarity.

As the images around the closest approach of H2 were returned from the spacecraft and viewed temporally, it was visually apparent that not only were there hundreds of bright particles in each frame but that the same particles seemed to persist in subsequently imaged frames and follow discrete paths during the encounter (see Fig. 1 for examples of the discrete particles and Fig. 2 for stereo images of the nucleus and particle distributions). The apparent motion of the particles comes primarily from the motion of the spacecraft cameras (translation and rotation) as they flew past the comet. Thus, the magnitude and direction of the apparent parallactic…
target—in this case, the fiducial features on H2 itself which we assume are fixed in space. A separate T must be constructed for each viewing geometry.

The main advantage of this method is that the conversion between image space and world space is physically based and direct (as the name implies). In addition, the physical basis of the calibration allows for extrapolation beyond the calibration volume (which is not the case, for example, with polynomial calibration routines). In its pure form above, the DLT does not accommodate for distortion effects. In order to compensate for these effects, we use the radial distortion corrections presented in Klaasen et al. (2008).

The calibration matrix is computed by first identifying a number of fiducial or control points on the comet in each image, and then solved using an iterative robust regression algorithm, as is commonly employed in computer vision applications (Hartley and Zisserman, 2004). For consistency and validation, we adopt the coordinate system used in the H2 nucleus shape model, as presented in Thomas (2012). The z axis is aligned with the long axis of the comet; y is approximately in the direction of spacecraft motion and x is approximately pointing towards the spacecraft during closest approach. Since we focus only on the images immediately surrounding the closest approach, we ignore the rotation of the comet and consider it as a fixed body in space. As an upper bound, the precessional motion has the long axis moving about $20^\circ$ per hour or $0.3^\circ$ per minute. Over a $2.5$ min window, the rotation of the comet was thus $0.75^\circ$.

3.2. Localization

While the HRI exhibits a theoretical factor of 5 improvement in resolution over the MRI, the MRI is in focus (without the need for deconvolution), and, more importantly, has a significantly higher temporal resolution during encounter (with $\sim5$ s between images during closest approach). As a result, many of the same particles can be located in multiple MRI frames; this is not the case for the HRI. We therefore focus on the MRI images for determination of the positions of the particles.

The localization procedure relies on “epipolar” geometry to identify particles in multiple frames (Fig. 3). In any given frame, particles are first located in image space. To solve for their three-dimensional position from stereoscopic parallax, the same particles must be located from at least one more viewing geometry. In this work, we require that the particle is imaged in at least three frames to ensure uniqueness; the frames are not required to be sequential to avoid issues with brightness variability. Note that while individual particles vary considerably in brightness over the encounter period on an image to image basis, the threshold sets a minimum brightness for the particles in at least three images.

First, we take a given frame and identify particles by convolving the image with circular masks the approximate size of the particles ($\sim3$ pixels). The center of the particle is calculated to sub-pixel accuracy by fitting the image intensity with a 3-point Gaussian curve. The search for matching particles in additional views can be restricted along “epipolar” line swaths in the other frames (discussed below).

In order to illustrate this concept, consider an individual particle identified in a reference frame. Although the 2D image-space $(u, v)$ location in the reference image is underdetermined and thus cannot be used to reconstruct the full 3D world-space solution alone, the line of possible image-space locations can be calculated by solving for the $y, z$ location of the particle over a range of $x$.
values. This can be thought of as mapping through the possible particle depths perpendicular to the sensor in the reference image. While the value for \( x \) is technically infinite in both positive and negative polarities, it is realistically restricted by the field of view—e.g., there are a finite range of \( x \) values that will map into the fields of view of other frames based on look angle and sensor/optical properties. In practice, we find that between subsequent image frames \( \pm 20 \text{ km} \) is the maximum \( x \) distance that the same particle can be identified. Considering the entire data set, no particles outside of \( \pm 80 \text{ km} \) would be seen in more than one frame. The possible epipolar solution set for an individual particle forms lines in each of the other frames when reconverted to image space coordinates; an additional buffer is included to account for reconstruction error and non-zero velocity during the search for matching particles (see Fig. 4).

Due to the large number of particles, this search is initially conducted by a combinatorics routine (e.g., Riordan, 2002) to identify the particle matches that are located in the same three-dimensional location in at least three images to uniquely solve for their positions. For example, if there are 10 possible candidate particle matches through the image sequence, the search is reduced to a 10-choose-3 (or better) number of 3D locations to validate a particle match. The utility of the epipolar geometry in this application is its ability to handle the temporally varying brightness of individual particles: if one particle falls beneath the threshold brightness for several frames, it can be located again when viewing conditions are more favorable. These effects are seen in almost all identified particles to varying degrees. The observing geometry also limits the ability to image

Fig. 3. Cartoon of the epipolar geometry employed in the reconstruction of the particle locations. The 3D location of a particle identified in only frame 1 of the illustrated sequence cannot be uniquely determined. The solution space can be mapped into an “epipolar line” in subsequent frames based on their respective viewing geometries. The correct particle identification between frames will match in reconstructed 3D coordinates throughout the encounter (within some reconstruction error or intrinsic motion of the particle).

Fig. 4. Example of the epipolar search and identification between subsequent frames. A displays a processed image of H2 and the control points on the surface (red \( \times \)‘s). A single particle is identified in image A (green square). B shows the next frame from the camera, with the same control points identified in red. The epipolar search area for the particle from A in frame B is denoted with a green dashed line. C is a magnification of the search line, with the matching particle identified (red circle and arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
a particle as particles outside of a certain distance from the focal point of the camera will appear as streaks.

The position of each particle is initially estimated from pairs of frames to determine the approximate location. This restriction implicitly sets the velocity of the particle to zero since the system is underdetermined with only two frames. However, if velocities are small, this approximation is fairly robust. Two methods were used to recursively determine the velocity and position of the particles once located. First, the approximate positions were determined from pairs of images as above. The positions were then fit robustly as a function of time using a bisquared weighting kernel to regress the position at closest approach and velocity of the particle.

Second, once the particle has been located approximately in multiple images, the particle location is re-fit with the additional three velocity vector components using:

$$\begin{align*} u &= \frac{T_1(x + V_xt) + T_2(y + V_yt) + T_3(z + V_zt) + T_4}{T_6(x + V_xt) + T_7(y + V_yt) + T_8(z + V_zt) + T_9} \\
v &= \frac{T_5(x + V_xt) + T_9(y + V_yt) + T_7(z + V_zt) + T_8}{T_6(x + V_xt) + T_7(y + V_yt) + T_8(z + V_zt) + T_9} \end{align*}$$

The addition of velocity requires at least three different views of the same particle to yield an evenly determined system of Eqs. (2,\(u,v\) coordinates × 3 images to solve for \(x,y,z,V_x,V_y,V_z\)); we restrict the analysis to particles with four or more views for this regression to allow minimization. The assumption of zero velocity is found to be fairly accurate for initial particle location since instantaneous velocities are low (although this is an obvious bias in velocities). The first method provides good agreement with the full regression, and is also resistant to errors in image space position (or a mismatched particle in one frame). No significant difference between the two results was evident by a t-test. Please see Section 4.2 for an analysis of errors associated with these measurements.

### 4. Results

The results presented here are calculated from 114 unique particle identifications (e.g., 3 or more detections) over the 31 images surrounding closest approach. The average number of images in which a given particle was detected was 13.9; this is approximately equal to the median number of detections (13.5). Of the

<table>
<thead>
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<th></th>
<th>Mean</th>
<th>Median</th>
<th>STD</th>
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</thead>
<tbody>
<tr>
<td>Distance (km)</td>
<td>5.07</td>
<td>4.56</td>
<td>2.72</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>2.41</td>
<td>0.73</td>
<td>5.01</td>
</tr>
</tbody>
</table>
located particles, 6 were detected in only the required minimum of 3 images; 2 particles were detected in the maximum of 29 images.

4.1. Statistics

The majority of the detected particles are located within 10 km from the center of the nucleus (in the body coordinate system presented in Thomas et al., 2012) (Fig. 5). Both the distance and velocity distributions are biased towards lower values (see Table 1 for overview of statistics). Fig. 6 presents the histograms of the distributions, both of which display significant skewness. It is also illustrative to examine the cumulative distribution functions or CDFs (Fig. 7). These CDF estimates reveal that \( 90\% \) of the measured particles are within 10 km of the nucleus. Similarly, \( 90\% \) of the measured particles are traveling slower than 10 m/s.

Fig. 7. Empirical cumulative distribution functions (calculated from Kaplan–Meier estimate (Kaplan and Meier, 1958)) of the calculated particle velocities and distances from the photogrammetric technique; 95% confidence intervals are overlaid as dotted red lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Distance of a selected set of particles from nucleus center versus time relative to closest approach. Connected diamonds mark the same particle identified in subsequent images. Note temporally varying nature as particles drop beneath the noise floor only to reemerge at a different viewing geometry.

Fig. 9. Histogram of the dot product of the normalized velocity vectors of the particles with the solar direction are presented to examine the directionality. The dot product of the normalized vectors is unity if the vectors are parallel, \(-1\) if antiparallel (as in flying away from the Sun) and 0 if orthogonal. The measured particles here do not seem to exhibit a strong anti-solar bias.

Fig. 10. Histogram of the dot product of the normalized velocity vectors of the particles with the “position” vector back to the center of the nucleus are presented to examine the directionality, as in Fig. 9. Most of the particles do not seem to be traveling directly away from the cometary nucleus.

The majority of the detected particles are located within 10 km from the center of the nucleus (in the body coordinate system presented in Thomas et al., 2012) (Fig. 5). Both the distance and velocity distributions are biased towards lower values (see Table 1 for overview of statistics). Fig. 6 presents the histograms of the distributions, both of which display significant skewness. It is also illustrative to examine the cumulative distribution functions or CDFs (Fig. 7). These CDF estimates reveal that \( 90\% \) of the measured particles are within 10 km of the nucleus. Similarly, \( 90\% \) of the measured particles are traveling slower than 10 m/s.

However, there are known selection effects at work here, since it is much easier to robustly determine the positions of low velocity particles near the nucleus because their apparent motions are relatively small due to parallax. The difficulty in matching particles between frames is further compounded by the temporal variability of brightness. Fig. 8 presents the location of particles through the encounter phase. Note that particles can appear in a frame, then disappear for tens of seconds before becoming visible again. Each detection requires the stereoscopic solution from a physical minimum of two different view points (and in general for our work here, three viewpoints to establish uniqueness). Thus, each point on the plot actually represents at least two separate detections. Systematic distance offsets with time are assumed to be due to the velocity of the particles.

The velocities of the particles are presented as a function of distance in Fig. 5. Any particles that have extremely fast velocities will not be measurable using this routine because each image is temporally distinct. Thus the stereoscopic reconstruction of a particle that has moved several hundred meters between sequential or close frames would yield different nonunique locations depending on which pairs of frames were looked at. We also explore the directionality of the particle motions by forming the normalized dot product of the velocity vector with both the solar vector and the “position vector” connecting the particle and the center of the nucleus (Figs. 9 and 10). The shape of the histograms may be an observation effect (explored below).

4.2. Error analysis

There are several sources of error in this analysis. First, while the Gaussian fitting technique is commonly found to achieve an accuracy in particle center estimation of ~0.1 pixel in many particle tracking studies (e.g., Nobach et al., 2005), the high degree of brightness variability of the particles studied here indicates that a homogenous spherical geometry is highly unlikely. The center of brightness may not be the center of inertia or mass for a tumbling, non-spherical particle; indeed, there should be an offset any time the phase angle is nonzero even for spherical particles (due to self-shading). Thus, the sub-pixel interpolation may not be accurate if the particle does not act as an Airy point source whose spatial reflectance is well approximated by a Gaussian. In real space equivalent, we note that at the closest approach, the MRI camera attained a resolution of ~7 m per pixel. Therefore, the highest precision possible (assuming that the sub-pixel interpolation is the only limiting factor; this is not necessarily an accurate assessment) is a positional uncertainty of ~70 cm in the 2D plane parallel to the sensor; this is greater than the expected particle diameter (Kelley et al., 2012).

Second, the locations of particles (and velocities) with respect to the nucleus are biased by the viewing geometry and illumination conditions. The majority of the particles are measured on the “side” (+y) and “above” (+z) the comet. This bias derives from the look angle and field of view of the MRI camera and the fact that there simply are few easily determinable particles in the solar direction (compounded by bright jets of material obscuring the point sources). See Fig. 11 for a representation of the particle locations along the trajectory. Lastly, by using the comet as the calibration object, we are necessarily requiring extrapolation beyond the calibration volume when measuring the particles. The measurement of small velocities (and their related directions) is very sensitive to these errors.

5. Discussion

The measured velocities of the particles are in general quite low. However, the escape velocity is ~0.3 m/s if the shape of the comet is simplified to a 0.6 km radius sphere of density 500 kg/m³ (Thomas, 2012). Most of the measured particles will thus not...
The variability can also be related to the effect of phase angles on the light curves of some near-earth asteroids may provide an analog to this variability. They are typically observed at high phase angles and not changes in the camera's perspective or phase interval, at least partially, the rotation of the particle and orientation changes apparent brightness based on the selection of the origin as the estimated center of mass of the nucleus; as a result, no particles should be detected within the face of the nucleus in this study.

From radar observations of H2, Harmon et al. (2011) found a characteristic velocity dispersion of ~4 m/s for >cm-scale dust particles, with evidence for the fastest particles traveling up to tens (~30) of m/s. Some of the highest particle speeds measured in this work are therefore close to those measured in the radar data; however, our characteristic velocities are lower. Jet formation models for H2 (e.g., Bruck Syal et al., 2012) predict speeds of 0.2–0.5 m/s, which is closer to the characteristic value for the majority of the particles measured here.

The high degree of temporal variability in brightness is interpreted as a geometric effect due to a heterogeneous or somewhat faceted particle surface that changes apparent brightness based on, at least partially, the rotation of the particle and orientation of the camera. During the inbound and outbound legs of closest approach, the spacecraft motion produced parallax shifts of only a few degrees, so the viewing geometry was nearly constant. Furthermore, the phase angle during the close approach only changed from 84° to 92° (with even less change during the inbound/outbound leg), which should have little effect on scattering properties. Thus, for at least some of the particles, the photometric variations must have been caused by changes in the grain (e.g., rotation of a "flat plate") and not changes in the camera's perspective or phase function variations. For periods near closest approach, where large parallax shifts occurred, we cannot preclude the possibility that the viewing geometry also played a role in the brightness variability. The light curves of some near-earth asteroids may provide an analog to this variability. They are typically observed at high phase angles, and their light curves can exhibit large amplitudes even though their shapes are not necessarily considered to be extreme. The variability can also be related to the effect of phase angles on backscattering from cometary dust. Particles seen at a phase angle of 0° are twice as bright as the same particle seen under 90°; steep increases occur at large angles, resulting in amplifications by factors as large as 2000 (Kolokolova et al., 2004). While images with the different wavelength filters were all obtained at larger distances from the nucleus, both before and after the large grains were resolved. The grains were only resolved in the images near closest approach, however, which were taken with the broadband CLEAR filter alone. Thus, there is no wavelength variation between images.

The directionality of the velocity vectors also hints at the dynamics of the particles. A non-rotating sphere would be pushed antiparallel to the solar vector due to radiation pressure; outgassing due to ice or other volatiles would further augment this effect. Radiation pressure effects, however, are not expected to play a significant role for such large particles. The absence of a robust correlation between either position vector or solar vector and the velocity of the particles may indicate that the particles are rotating, and thus heating and cooling as they tumble. If the particles were outgassing as well, as is expected (A'Hearn et al., 2011), the acceleration vector would not be parallel to the solar vector but would be offset by some angle depending on geometry, possibly pushing the particles in a generally more orthogonal direction. This directionality is consistent with the >52° antisolars inferred by Harmon et al. (2011). However, it is also possible that the particles are rotating rapidly compared to the thermal timescale, and thus should outgas more symmetrically. If this is the case, then particle motions may be largely driven by hydrodynamic effects at the earliest stages of ejection.

### 5.1. Distant particle detection

While the photogrammetrically detected particles described here are all fairly close to the nucleus, evidence for dust particles exists considerably farther out. Examination of high rate spacecraft telemetry reveals nine attitude disturbances that are not attributable to spacecraft maneuvers (such as turns, navigation updates, filter wheel motions, etc.) These disturbances are interpreted as dust impact events on the spacecraft. In each case, a spacecraft angular momentum "step," or jump is observable simultaneously in multiple spacecraft axes (e.g., Fig. 12). The rotational axis of each disturbance is found to be roughly perpendicular to the comet relative velocity.

Exact particle masses cannot be determined from the spacecraft angular momentum changes without knowing the offset between the impact point and the spacecraft center of mass. By assuming an impact offset consistent with the spacecraft dimensions, representative values can be computed. Assuming a 1 m impact offset, 280 kg m² spacecraft moment of inertia and a perfect inelastic collision, computed particle masses for the observed events range from 0.017 to 0.19 mg.

Depending on the construction materials at the exact point of impact, however, substantial enhancement of the momentum transfer is possible. Hypervelocity impact events can multiply the

### Table 2

Estimated particle masses from telemetry transients. Particle masses are computed using inelastic momentum transfer and with the 6× momentum enhancement assumed for impacts onto the aluminum frame at varying realistic distances from the center of mass of the spacecraft. All masses are in mg.

<table>
<thead>
<tr>
<th>Event time (spacecraft clock)</th>
<th>S/C range (km)</th>
<th>Particle mass (0.5 m offset)</th>
<th>Particle mass (1 m offset)</th>
<th>Particle mass (2 m offset)</th>
<th>Particle mass (6×: 0.5 m offset)</th>
<th>Particle mass (6×: 1 m offset)</th>
<th>Particle mass (6×: 2 m offset)</th>
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<td>0.004</td>
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</table>

momentum transfer considerably over basic inelastic mechanics because the crater ejects target material in the opposite direction of the impact vector. This phenomenon has been previously characterized for the speeds expected here (e.g., McDonnell et al., 1984). Assuming a vertical impact (e.g., orthogonal to the target), we adopt a momentum enhancement multiplication of 6 (6 × hereafter) at the 12.3 km/s flyby velocity for impacts into bare aluminum (such as spacecraft frame) (McDonnell et al., 1984).

Computed particle masses (assuming 6 × enhanced momentum and 1 m offset) range from 0.003 to 0.032 mg. The minimum detectable particle mass from attitude telemetry using this method and assuming a 6 × enhanced impact on the spacecraft High Gain Antenna (offset = 2 m) is estimated to be 0.001 mg (see Table 2). There is fairly little data on the momentum multiplication factor for different densities at high impact velocities (this is an experimental limitation, since higher speed impacts were attained with the use of an electromagnetic dust accelerator). However, if the grains that hit the spacecraft were composed of pure ice, the inferred size of the particles would be shifted slightly upward, since a larger ice projectile would be needed to create the same torque impulse at a given impact velocity as a denser silicate grain. Porous materials of even lower densities would also increase the theoretical size of the particles. We note that ice or porous materials would alter the shock coupling which may serve to diminish the momentum enhancement factor.

Since the telemetry does not reveal many of these events, the dust distribution is interpreted to be quite sparse and small at the flyby distance. We also note that if impacts occur on the multi-layered insulation (MLI) or other “soft” material, the momentum transfer might instead be reduced under that expected in inelastic collisions, and thus drop under the sensitivity of detection. We note that the larger grains detected and measured photogrammetrically are several orders of magnitude larger than the particle sizes inferred from the spacecraft attitude changes.

6. Conclusions

The Deep Impact Spacecraft flyby of Comet 103P/Hartley 2 revealed a field of debris composed of fine grained dust, ice, and hundreds of discrete larger decimeter-sized particles enveloping the nucleus. Drawing from computer vision techniques, a selection of the brightest particles were identified and located in 3D space in nucleus. Drawing from computer vision techniques, a selection of the brightest particles were identified and located in 3D space in

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2012.09.030.

References


