Shape, density, and geology of the nucleus of Comet 103P/Hartley 2


aData from the Extrasolar Planet Observation and Deep Impact Extended Investigation (EPOXI) mission show Comet 103P/Hartley 2 is a bi-lobed, elongated, nearly axially symmetric comet 2.33 km in length. Surface features are primarily small mounds <40 m across, irregularly-shaped smooth areas on the two lobes, and a smooth but variegated region forming a “waist” between the two lobes. Assuming parts of the comet body approach the shape of an equipotential surface, the mean density of Hartley 2 is modeled to be 200–400 kg m$^{-3}$. Such a mean density suggests mass loss per orbit of >1%. The shape may be the evolutionary product of insolation, sublimation, and temporary deposition of materials controlled by the object’s complex rotation.

1. Introduction

After carrying out an impact experiment on Comet 9P/Tempel 1 (A’Hearn et al., 2005a) the Deep Impact mission’s flyby spacecraft was retargeted to Comet 103P/Hartley 2 as part of an extended mission named EPOXI. Compared to Deep Impact’s first target, Hartley 2’s nucleus is one-fifth the size yet produces a similar amount of outgassing at perihelion (Groussin et al., 2004; Lisse et al., 2009; Meech et al., 2011). This high level of activity made 103P/Hartley 2 an especially interesting target, and for expectations that its surface features would differ from those of Tempel 1. Closest approach to Hartley 2 was 694 km at 13:59:47.31 UTC on 4 November 2010, 1 week after perihelion passage and 1.064 AU from the Sun. The images confirmed that its surface is very different from that of Tempel 1, and indeed from the other comets so far visited by spacecraft (A’Hearn et al., 2011; Schultz et al., 2011).

We use the image data to produce a shape model (refined from that reported in A’Hearn et al. (2011)) and surface feature maps. These products are then used to investigate the processes effective at the comet’s surface, its mean density, and some aspects of its evolution.

2. Data and methods

Because the Hartley 2 encounter has been described in depth in A’Hearn et al. (2011), we summarize only the most pertinent imaging instrumental details here. The Deep Impact spacecraft and its instruments are described in A’Hearn et al. (2005b), Hampton et al. (2005), and Klaasen et al. (2008). Most of the work reported here has used the EPOXI Medium Resolution Instrument (MRI) camera data; these have a pixel scale of ~7 m at the closest approach of 694 km. The EPOXI High Resolution Instrument (HRI) nominally produces images at ~5 times better resolution than MRI, but was found to be out of focus after launch (Klaasen et al., 2008). Deconvolution (Lindler et al., 2012) can render some of these images suitable for studying forms smaller than are visible...
Good control of much of the rest of the shape is provided by pro-
adjustments (Thomas et al., 2002). There are 244 manually mea-
sured points in the images relies upon stereo control points with image pointing
less than 1 pixel at the ends of the object.

Table 1
Characteristics of Hartley 2.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>5.24 km²</td>
</tr>
<tr>
<td>Volume</td>
<td>0.809 ± 0.077 km³</td>
</tr>
<tr>
<td>Mean radius</td>
<td>0.58 ± 0.018 km</td>
</tr>
<tr>
<td>Diameter range</td>
<td>0.69–2.33 km</td>
</tr>
<tr>
<td>Gravity</td>
<td>0.0019–0.0044 cm s⁻² (if mean density = 300 kg m⁻³)</td>
</tr>
<tr>
<td>Model moments</td>
<td>5.302 × 10⁴, 31.26 × 10⁴, 31.92 × 10⁴ m²</td>
</tr>
<tr>
<td>Model moment ratios</td>
<td>A/C: 0.166 ± 0.004, B/C: 0.979 ± 0.002</td>
</tr>
<tr>
<td>Body model moment orientations</td>
<td>A: 307.5°, 207.56°; B: 0.05°, 106.14°; C: 0.25°, 16.14° E</td>
</tr>
<tr>
<td>Long axis at closest approach</td>
<td>RA: 226.12°, Dec: 39.37°</td>
</tr>
<tr>
<td>Minimum moment at closest approach</td>
<td>RA: 225.92 ± 0.9°, Dec: 39.60 ± 0.7°</td>
</tr>
<tr>
<td>Intermediate moment at closest approach</td>
<td>RA: 330.0°, Dec: 16.3, ±12° along arc perpendicular to minimum moment</td>
</tr>
</tbody>
</table>

Most useful MRI data were obtained within a range of 1600 km
of the comet (16 m/pixel) and span phase angles of 80–94°. A few
HRI images were useful out to ranges of ~2500 km. Navigation
data in the form of “SPICE” kernels (Semenov et al., 2004; Semenov
and Acton, 2006) are the basis for all geometric work on the comet.

Most useful MRI data were obtained within a range of 1600 km
of the comet (16 m/pixel) and span phase angles of 80–94°. A few
HRI images were useful out to ranges of ~2500 km. Navigation
data in the form of “SPICE” kernels (Semenov et al., 2004; Semenov
and Acton, 2006) are the basis for all geometric work on the comet.

Mapping of features and projection of images uses image cubes
that store latitude, longitude, radius, incidence, and emission at
each pixel. Line and sample coordinates of features marked in
the images or the image data themselves can then be arbitrarily
projected.

Quantities such as gravity and slope are calculated with an as-
sumed mean density and rotation vectors. We discuss the determi-
nation of the nucleus’ mean density in detail in Section 5.

“Topography” is calculated as dynamic height, the surface poten-
tial energy divided by an average acceleration (Vanicek and Krak-
iwsky, 1986; Thomas, 1993) which is close to the height above a
reference equipotential. The dynamic heights also depend upon
mean density and rotation rate and are studied in Section 5.

Mapping uses a prominent feature as a prime meridian: a
dark spot, actually including part of a shaded side and shadow
cast from a 20-m high mound. The map coordinate system used
here is oriented on the basis of the bi-lobed shape: the long axis
is taken to be the latitude direction. Given the complex and chang-
ing rotation (Belton et al., 2012) latitudes and longitudes cannot be
tied to any rotation element. Our maps are not intended as IAU
proposals.

The cylindrical mapping of such an elongate, bi-lobate object
has distorted areas no matter the orientation. Here we use both
simple cylindrical and a pseudo-equal area projection to better
handle high latitude data. This method simply measures the dis-
tance along latitude lines from a reference longitude, and scales
the north–south coordinate to the average length of a longitude
line. This scheme is particularly suited to a nearly axially-symmet-
ric object such as Hartley 2 because the length of the longitude
lines varies only slightly.
3. Overall results

Global characteristics of Hartley 2 are listed in Table 1. Preliminary values, close to these, were presented in A’Hearn et al. (2011); updates to the shape have largely been local changes of <20 m from addition of control points and more limb control. Fig. 1 presents a stereo view at the best MRI resolution which covers most of the visible object. Fig. 2 shows coverage for data that control the calculation of the shape, as well as views of the resulting shape model shaded by the dynamic heights. The mean radius (radius of a sphere of equivalent volume) of 0.580 ± 0.018 km found here is indistinguishable from that calculated before encounter by Lisse et al. (2009) using Spitzer data to determine the effective radius of the cross-section at the time of observation. This bi-lobed object has near rotational symmetry: calculated moments, assuming a homogeneous interior, have relative values of 1.000, 0.979 ± 0.002, 0.166 ± 0.004. These model moment ratios are unusually but not uniquely symmetric. For comparison, the model moment ratio B/C for Tempel 1 is 0.931, it is 0.982 for asteroid Eros, and it is 0.980 for satellite Epimetheus. Several other Saturnian small satellites’ B/C range from 0.819 to 0.886 (These values calculated by PT). That Hartley 2 is not exactly symmetric is noticeable in Fig. 1 when carefully viewing the larger lobe. Nonetheless, this object does not have the asymmetries that are seen on many impact-shaped objects (Thomas, 1989). Note that an object such as Eros can have moment ratios of nearly 1 while having a distinctly banana-like shape.

4. Terrain types and surface features

The surface of Hartley 2 is approximately divisible into two rough lobes connected by a smooth “waist” (Figs. 1 and 2). Surface maps are shown in Figs. 3 and 4. In detail the surface combines varying distributions of mounds generally less than 30 m in any dimension, and substantially smoother terrain (at 7 m/pixel). While the latitudinally confined waist is the largest smooth area, other smooth areas of irregular outline occur in parts of the larger lobe.

4.1. Mounds

The roughness of Hartley 2 derives from the presence of mounds, mostly only a few pixels across, and most of which are crudely equidimensional. However, a few of these are unusually elongated, either nearly normal to the surface or at low angles to the surface (Fig. 1). There are a few spires greater than 40 m in height, one of which appears in stereo viewing to be angular in shape with a probable overhang (upper part of Fig. 1 near terminator). Views such as Fig. 1 suggest there are albedo differences among the mounds, but estimating reliable albedos from marginally resolved features with a variety of photometric geometries demands extreme caution. The qualitative mapping did divide
mounds by apparent relative brightness (Fig. 3), though for most purposes one should lump them together as one population of features. The size distribution of mounds (Fig. 5) suggests a large population smaller than the available resolution.

4.2. The waist

The distinctive waist (Figs. 1 and 6) is visible in images between longitudes 90–280°E and latitudes 2°S–22°N to ~60°N. Silhouettes in both HRI and MRI data show this shape occurs over nearly the full circumference of the object (Fig. 6). The surface is variegated at horizontal scales of 15–30 m. The markings in the waist, mostly only 2–3 pixels across, are repeatable image-to-image and are well-defined in stereo pairs (Fig. 7a). Thus these subtle forms are real and not simply noise. Patterns of different albedo also exist on the 100–200 m scale and suggest digitate outlines (Fig. 7a), especially near the margins. A darker region between ~10 and 40°N occupies most of the visible longitude range but fades at about 70°E. This limitation may reflect an incidence angle effect at values >60°.

The smoothness of the waist may be important in questions of its formation mechanism. Fig. 6 shows limb profiles measured to ~0.15 pixels precision (~1 m in the best images) by software specifically designed for edge detection (Dermott and Thomas, 1988). Repeatable deviations of ~2 m occur within these profiles. As with any limb profile the observed edge is a skyline smoother than a straight topographic profile over the position of the limb. Most deviations are under 1 m. The very high incidence angle region near the east end of the waist is limited in the applicability of shadows to measuring topography because some of this area is shadowed by protuberances that are part of the small lobe. The solar direction does have a westward component near the terminator, so some of the waist is seen at incidence angles above 86°. Irregularities in the terminator of ~10–15 m suggest topography of at
least \( \sim 1 \) m in height in this region. Thus, while the waist is smoother than the rest of the object, formative processes must cause, expose, or preserve topography of up to \( 2 \) m in height (and possibly more) on local scales up to \( 30 \) m in horizontal extent.

4.3. Other smooth areas

The large lobe has several (7 or more) irregularly-shaped areas of smoother and slightly darker appearance than the average surface of Hartley 2 (Figs. 2 and 7b). These darker areas are flanked by slightly brighter materials of varying extent. In combination with the mounds these areas comprise a sequence from the center outward of dark smooth material, brighter smooth areas, and mound–dense regions. The stereo pairs (Fig. 7b) show that these dark smooth regions range from elongate and irregular, to almost regular polygons. With strong contrast enhancement they show mottling on roughly the same horizontal scale of 15–30 m as seen in the waist, although they are less prominent than those markings within the waist.

4.4. Jets

Jets made visible by entrained dust and ice particles are prominent features of the region near the nucleus. Although the jets are not surface features, the approximate base locations are plotted in Fig. 3. These were mapped by interactive stereo viewing and plotting results on the projected shape model in single views of the surface. Because the contrasts of the jets change with viewing, and the background in most areas under the jets is variegated and rough, these positions, and even the number of jets, is subject to some interpretation. The basic occurrence pattern is reliable, and shows the association of jets with the rougher areas and mounds, and their avoidance of the smooth areas, as noted by A'Hearn et al. (2011) and Syal et al. (2012). Accurate measurement of their dimensions is beyond this work, but most are 3–5 pixels wide in the 7-m/pixel data. Detailed modeling of possible jet formation and relation to general surface evolution is reported in Syal et al. (2012).

4.5. Other patterns and forms

On the larger lobe, the region from \( \sim 260–320^\circ \) E to \( \sim 20–70^\circ \) N has somewhat rougher mound topography, more small spire-like mounds, and displays a somewhat higher albedo and bluer colors (Li et al., 2012) than the middle part of this lobe. The color differences appear to arise from a greater exposure of water ice (Sunshine et al., 2011; Li et al., 2012) and might relate to this area being near the morning terminator, the morphologic differences would not arise diurnally. In fact, there is a smaller region of somewhat similar increased roughness in the region \( 30–80^\circ \) E. Thus, although topographic type varies crudely along the long axis of this object, considerable variation exists longitudinally.

5. Inferring a mean density

5.1. Inferences from averaged quantities

The distinctive, smooth profile of the waist of the object was used by A'Hearn et al. (2011) and Richardson and Bowling (2012) to infer a mean density range for Hartley 2 using some assumptions. First, the smooth form was assumed to be at or close to an equipotential, presumably the result of depositional filling and smoothing a low area. Second, a simple 18-h rotation period was assumed about the maximum moment direction at the time of encounter. Third, the interior was assumed to be homogeneous in density. Minimizing the variation of fractional potential energy over the area of the well-imaged waist suggested a mean density of \( 220 \) kg m\(^{-3}\) (A'Hearn et al., 2011) and \( 140–520 \) kg m\(^{-3}\) (Richardson and Bowling, 2012). Here we use the updated shape model, slightly different definitions of the waist area, and considerations of whether implications in the spin have practical effects to interpret the mean density.

The most important additional concern is the comet's complex and changing rotation (A'Hearn et al., 2011; Belton et al., 2012). First, the primary period was rapidly increasing at the time of encounter, approximately 0.1% per period; where the period was \( \sim 16 \) h only 60 days before encounter (Meech et al., 2011; Belton et al., 2012). Surface features are unlikely to evolve at meters/day (see Section 6.1), and thus the shape we measure and attempt to model would have formed over a considerable interval of time before the flyby. Thus, the applicable primary period would be 16 h or possibly even less. Additionally, the complex spin imposes a roll about the long axis, which for our purposes may be thought of as having two effects: (1) The primary spin pole moves; in our mapping the spin pole would move through different longitudes, varying the rotational accelerations added to the gravitational accelerations. (2) The roll slightly reduces the relative gravitational topography along the longitude lines (along the cross profiles of the waist); For a 27.8 h roll period relative topography from the middle of the waist (latitude 40°N) to the northern edge (60°N) de-
creases by 1 m relative to a no-roll situation. Moving the spin pole position has some effect on the relative heights of points within the waist relative to the south pole because the waist is not perfectly circular along latitude lines (typically 25–30 m difference in radius from 60°E to 300°E along latitude lines in the waist). The north–south difference in dynamic heights along a particular longitude line varies by less than 1 m with the change in spin pole location. Thus, we can make comparisons based on a nominal spin pole location as the effects of the roll are effectively much smaller than is our ability to discriminate topography. We make these comparisons of heights for different densities and spin rates.

For each mean density we calculate the potential energy at the surface (Thomas, 1993), the effective acceleration, its angle to the surface normal (slope), and the dynamic height (Vanicek and Krakiwsky, 1986) which uses an area-averaged acceleration to scale the potential energy values. We tested several areas for the variations in slope and potential: the whole object, the darker part of the waist (Fig. 3), the whole mapped waist, and the entire 360° longitude range between 10°N and 60°N. For these different areas of the surface we find the area-averaged slopes, and the area-averaged variance of the potential, the latter scaled for the average potential because different densities impose different absolute potentials.

We made model predictions assuming primary rotation periods of 14, 16 and 18 h, and for bulk nuclear mean densities between 120 and 800 kg m$^{-3}$. Of 14, 16 and 18 h, and for bulk nuclear mean densities between 120 and 800 kg m$^{-3}$, of 14, 16 and 18 h, and for bulk nuclear mean densities between 120 and 800 kg m$^{-3}$, because different densities impose different absolute potentials.

Table 2

<table>
<thead>
<tr>
<th>Area</th>
<th>Density from slope (kg m$^{-3}$)</th>
<th>Density from potential variance (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>300</td>
<td>265</td>
</tr>
<tr>
<td>Waist</td>
<td>340</td>
<td>NM</td>
</tr>
<tr>
<td>Dark</td>
<td>NM</td>
<td>NM</td>
</tr>
<tr>
<td>Period = 16 h</td>
<td>NM</td>
<td>NM</td>
</tr>
<tr>
<td>NM = no minimum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8. Variation of slope and potential as a function of mean density. Left: Average slope, degrees, as a function of mean density for the whole object, the entire waist (see Fig. 2), and the darker portion of the waist (Fig. 2). Right: variation of potential energy for same areas as in (a).

5.2. Insights from topographic profiles

We attempt to refine the density inferences by reference to topographic profiles shown in Fig. 9. These show north–south profiles of dynamic heights at two longitudes for the 16-h rotation period. These profiles emphasize the variation of topography within the waist and the range of mean densities that come close to making part of the waist nearly flat, but which still leave noticeable slopes at other locales.

The simplest approach is to see what mean density gives the waist area (generally on these plots between x-axis values of 0.05 and 0.80 km) the flattest profiles; this value is ~230–240 kg m$^{-3}$. Values of 200–300 kg m$^{-3}$ also appear consistent with a low, relatively flat waist region. These profiles also illustrate that global relief is minimal for densities near 250 kg m$^{-3}$.

Do the possible geological interpretations of the waist warrant matching an equipotential? This smooth surface might represent an equipotential surface, that is, it might be an area of ponding of loose material that cannot support slopes and is all close to the same potential. It might represent a relatively low area that is accumulating materials but has not entirely been flattened. It is bounded on the south by a transition to rougher terrain, sometimes gradually, at latitudes ranging from ~0 to ~30°N. The northern boundary is gradational over ~100 m at latitudes of ~56–60°N. The waist does not have a sharp boundary such as do “ponds” on Eros (Robinson et al., 2001) or the Muses Sea on Itokawa (Fujiwara et al., 2006). Although ponds are visibly distinct, there is a suggestion that some of the ponds on Eros are not completely “flat” (Roberts et al., 2012). The waist on Hartley 2 does not show flow fronts or other likely indicators of discrete flow units. Thus, while the images suggest low-slope processes, there is no clear geological restriction on how flat this region is.

The other darker smooth areas in the large lobe might be expected to either be flat, locally low, or perhaps show slopes indicative of a flow, especially for the elongate one at ~50°S, and 338–38°E (Fig. 3). These features occur in slightly lower regions than their surroundings, though the differences are largely <15 m. We note that the rotational light curves of H$_2$O and CO$_2$ (Besse et al., 2011) imply that the smaller lobe is much more active than the larger lobe so that transfer of material from the smaller lobe to these

Note that the rotational light curves of H$_2$O and CO$_2$ (Besse et al., 2011) imply that the smaller lobe is much more active than the larger lobe so that transfer of material from the smaller lobe to these
have a different density from that of the surface regions. Investigation of these parameter spaces is left for later study. The simplicity of the current model emphasizes that the inferred density of 200–400 kg m$^{-3}$ probably is an optimistic rendering of the uncertainty. By far our greatest concern with this modeling apart from assumptions of geologic processes, is that it is a static model of dynamic processes: the rotation and the surface accelerations have been changing, and the surface has been changing also. The observed shape is almost certainly an integrated effect of processes that has not reached, nor will it likely reach, an equilibrium form.

5.4. Meaning of a very low density

A density of 300 kg m$^{-3}$ would require a high mean nucleus porosity, >70%, that could originate by inefficient packing of elongate or irregularly shaped particles and/or macroscopic voids. Particle densities would be roughly 930 kg m$^{-3}$ for H$_2$O, 1500 kg m$^{-3}$ for CO$_2$, ~800 kg m$^{-3}$ for CO and 2500–3500 kg m$^{-3}$ for refractory, rock-forming materials (e.g., silicates, metal sulfides, amorphous carbon). An upper limit of mean density of 520 kg m$^{-3}$ would require ~45% porosity for water ice particles, and >50% for modestly more dense particles such as CO$_2$ ice or silicates. The ejection of loose clumps of material that rapidly disaggregate (A’Hearn et al., 2011) is consistent with a low-density assemblage. The different terrains on the surface indicate the operative processes sort materials and/or have different stages of development. The different relative amounts of CO$_2$ and H$_2$O (Besse et al., 2011; Feaga et al., 2011) also indicate either sorting of materials, global inhomogeneities, or different stages of processes in different regions of the comet nucleus.

6. Changing Hartley 2

6.1. Mass loss by Hartley 2

In order to estimate the total mass loss by Hartley 2 at a given apparition, we consider primarily the observations of the water release as determined from Ly-$\alpha$ measurements with the SWAN instrument on the Solar and Heliospheric Observatory (SOHO) (Combi et al., 2011a,b). These data cover the 1997 and 2010 apparitions and show clearly that the activity decreased by roughly a factor 3 from 1997 to 2010. The SNR is much better in 1997 so we use that apparition to integrate around the orbit.

In the 1997 apparition, the water production peaked at log($Q$) = 28.55 molecules s$^{-1}$ a few days after perihelion. We have carried out a numerical integration over the observed portion of the orbit using linear interpolation between each of the data points and we have also analytically integrated the power law obtained by assuming straight lines, eyeball fitted in log($Q$) vs. log($\Delta t$) (steeper before perihelion than after; $\Delta t$ is time since perihelion). The two approaches agree within 20%. We have extended the range in heliocentric distance slightly using two points based on OH measurements supplied by Knight and Schleicher (2012) at 50 days pre-perihelion, log($Q$) = 27.64 s$^{-1}$, and 66 days post-perihelion, log($Q$) = 27.69 s$^{-1}$, both nearly an order of magnitude below the peak. To estimate the contribution further from perihelion, Meech et al. (2011) show from water-sublimation models, that the heliocentric light curve data (scattered light measurements from the dust) is consistent with the activity beginning ~450–500 days pre-perihelion near 4.3–4.2 AU. This is consistent with what was seen in previous apparitions by observers as compiled by Ferrin (2010). Post-perihelion activity continued through aphelion, turning off between 200 and 400 days post-perihelion (near $r$ = 5.6 AU). Although Meech et al. (2011) suggest that this continued presence of grains in the coma is from CO$_2$ outgassing, we as-
sume here that the continuation through perihelion is due primarily to the rapidly increasing lifetime at large heliocentric distances of the icy grains that were released earlier and seen so prominently at this apparition (A'Hearn et al., 2011) and that the outgassing stops at 400 days. This yields a conservative lower limit on the total mass loss. If the average production rate during the decline to zero is as high as $10^{24} \text{s}^{-1}$, roughly 1/3 the value suggested by the apparent magnitude at 250 days, it adds only about 2% at each end to the total mass loss. This computation yields a conservative lower limit of the total water release of $1.5 \times 10^{35} \text{molecules}$ or $4.5 \times 10^{12} \text{g}$. From measurements during the flyby we know that CO$_2$ is about 30% by mass of H$_2$O. If we assume dust/gas = 1, the total mass loss during the 1997 apparition was $1.2 \times 10^{13} \text{g}$. During the 2010 apparition, therefore, it was roughly $4 \times 10^{12} \text{g}$. These numbers are very sensitive to the dust/gas ratio, a poorly determined parameter for all comets (due to the mass of dust being dominated by the largest grains in many comets), but half this value (the ices) is a solid lower limit and the value could range up to 2 or 3 times larger than the value above.

Using the surface area from Table 1, the mass loss in 1997 corresponds to $\sim 2300 \text{kg m}^{-2}$. For a bulk density of 300 kg m$^{-3}$, this value corresponds to a loss of 7.7 m of material everywhere on the surface. In terms of the upper range of the density from Richardson and Bowling (2012) (and a more typical density for other, better determined nuclei) a mean density of 520 kg m$^{-3}$ would suggest loss of 4.4 m per orbit. Using the volume from Table 1, and a density of 300 kg m$^{-3}$, the mass loss during the 1997 apparition was roughly 5% of the total mass of the nucleus and thus about 2% of the total mass during the 2010 apparition. An upper density value of 520 kg m$^{-3}$ would suggest a loss nearer 3% of the nuclear mass in 1997 and 1% in 2010. Even allowing for a factor of a few uncertainty due to the unknown dust/gas mass ratio, this mass loss, both as an average depth and as a fraction of the mass of the nucleus, is far higher than that found for the much larger nucleus of 9P/Tempel 1 ($\sim 1/3 \text{m/orbit}$ or $\sim 3 \times 10^{-4} \text{mass/orbit}$; Thomas et al., 2012).

The above calculations are average amounts over the entire surface. However, all the evidence from the flyby (A'Hearn et al., 2011) suggests that much of the material is lost from sub-surface outflows that are localized, so collapse features might be the expected expression one would see in images from different apparitions, perhaps analogous to those seen near the smooth flow on 9P/Tempel 1 (Schultz et al., 2011). However, collapse forms are not obvious in the images. Perhaps some of the dark areas might be remnants of collapse of connected large voids partially filled and smoothed by material formerly above the voids ("crust") or partially covered by some materials mobilized near the surface by other vents.

The presence of mounds may suggest eruptive and constructive mechanisms at work, and the ejection of particles that subsequently supply much of the mass loss by sublimation (A'Hearn et al., 2011; Harmon et al., 2011; Kelley et al., 2012) indicates an environment rich with material that could form brighter local deposits. There is the possibility that the average surface is losing material while some of the mounds undergo deposition and upward growth. The height of the mounds (generally <30 m; Section 4.1) might be the net result of loss and growth before the mounds collapse. This height might reflect the strength of the mounds, which can be crudely estimated based on $\rho g h$, where $\rho = 300 \text{kg m}^{-3}$, $g = 4 \times 10^{-2} \text{ms}^{-2}$, and $h = 3 \times 10 \text{m}$, assuming a density at the low end of our mean values. This approximation gives a value of 0.4 Pa. Such a weak material would be consistent with local accumulation of what might be close to snowflakes. Given the small relief elsewhere on the comet nucleus, strengths estimated using these assumptions for materials anywhere on this object will be very low.

The high rate of mass ejection does suggest there should be some small, low-velocity fraction that may not initially escape. This material might be distributed widely over the nucleus, and could possibly flow with the tenuous gasses evolving from ice particles into the gravitationally lower regions. Such material would have essentially zero strength and be consistent with minimal topography on a very low-gravity object.

7. Summary

Hartley 2 is distinguished by a nearly axially symmetric, bi-lobed shape. An extremely active comet partly by virtue of expelling solid water--ice particles, its surface may suffer average loss of a few meters per orbit. Its surface features, chiefly mounds <30 m in dimension, relatively darker smooth areas, and a waist...
with local topography <2 m do not easily compare to obvious erosional and depositional forms such as the pits and smooth deposits on Tempel 1. The smooth shape, and especially the waist, suggest processes whose net effects reduce topography on horizontal scales of >100 m. The shape combined with assumptions of smoothing processes suggests a mean density of 200–400 kg m\(^{-3}\). This mean density implies loss of >1% of the nuclear mass per orbit. The axial near symmetry suggests no significant role for random events such as craters but does suggest interacting roles for insolation, spin, and gravity.

Acknowledgments

Most of the work for this paper was funded by NASA, through Contract NNM07AA99C to the University of Maryland from NASA’s Discovery and New Frontiers Program Office. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Technical assistance provided by A. Quick, K. Consroe, R. Rich Goldweber, and C. Jackman. Two reviewers helped find mistakes and improve the presentation.

References