EPOXI at Comet Hartley 2

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Understanding how comets work—what drives their activity—is crucial to the use of comets in studying the early solar system. EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation) flew past comet 103P/Hartley 2, one with an unusually small but very active nucleus, taking both images and spectra. Unlike large, relatively inactive nuclei, this nucleus is outgassing primarily because of CO2, which drags chunks of ice out of the nucleus. It also shows substantial differences in the relative abundance of volatiles from various parts of the nucleus.

Comets are the fundamental building blocks of the giant planets and may be an important source of water and organics on Earth. On 4 July 2005, the Deep Impact mission carried out an impact experiment on comet 9P/Tempel 1 (1, 2) to study differences between the comet’s surface and the interior. Although the impactor spacecraft was destroyed, the flyby spacecraft and its instruments remained healthy in its 3-year, heliocentric orbit after completion of the mission. The Deep Impact flyby spacecraft was re-targeted to comet 103P/Hartley 2 as part of an extended mission named EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation).

The flyby spacecraft carries the High Resolution Instrument (HRI), which combines a visible-wavelength camera with a pixel size of 2 μrad and a set of filters with a near-infrared (near-IR) (1.05 to 4.85 μm) spectrometer with an entrance slit of 10 μrad by 256 μrad, with 512 spatial pixels along the slit. Spectral maps were created by scanning the slit across the comet while taking a sequence of spectra. The Medium Resolution Instrument (MRI) has a pixel size of 10 μrad and a different but overlapping set of visible-wavelength filters (3, 4).

Encounter with Hartley 2

The closest approach to Hartley 2 was 694 km at 13:59:47.31 UTC on 4 November 2010, 1 week after perihelion passage and at 1.064 astronomical units (AU) from the Sun. Flyby speed was 12.3 km s−1, and the spacecraft flew under the comet with a somewhat northward trajectory in a solar system reference frame. Because instruments are body-mounted on the spacecraft, the spacecraft rotated to keep the instruments pointed at the comet. Observations of the comet were carried out for 2 months on approach (5 September to 4 November) and for 3 weeks on departure (4 to 26 November), during which more than 105 images and spectra were obtained.

Prior remote sensing showed that Hartley 2’s nucleus has an average radius 1/5 that of comet Tempel 1’s nucleus (5, 6), yet it releases more gas per unit time at perihelion, even when allowing for the smaller perihelion distance of Hartley 2 (1.059 versus 1.506 AU). This puts Hartley 2 in a different class of activity than that of Tempel 1 or any of the other comets visited by spacecraft (fig. S1). The two comets have very different surface topography (Fig. 1), but whether the different topography is related to the hyperactivity is still being investigated.

The Nucleus

Spin state and variations. The rotation state of the nucleus distinguishes the morning from the evening terminator and, in comparison with longer-term coma observations, allows the number and relative strengths of active areas to be determined. Knowledge of the nuclear spin can also put constraints on internal distribution of mass in the nucleus, internal energy dissipation, and the magnitude of the net torque.

The large variations in brightness in Fig. 2, reduced to a measure of the amount of dust leaving the nucleus, show a period of roughly 18 hours, but the spacing of peaks in the light curve shows a clear pattern that repeats every three cycles. We interpret this [supporting online material (SOM) text] as an excited state of rotation, with each cycle corresponding to precession of the long axis of the nucleus around the angular momentum vector, with a period of 18.34 hours at encounter. The pattern of three cycles is due to an approximate commensurability between this precession and the roll around the long axis with a period of 27.79 hours (55.42 hours is also possible; the ambiguity does not affect any conclusions in this paper). The orientation of the angular momentum vector is not yet tightly constrained but is within 10° of being perpendicular to the long axis. This excited state also implies a nodding motion of the long axis relative to the angular momentum vector, but the observed near-axial symmetry of the shape limits this to an amplitude of <1°. The precession period is increasing at 0.1% per period near perihelion, which is unusually high but not unprecedented rate of change for a comet. The roll period is decreasing. These changes are
presumed to be due to torques produced by the outgassing.

Nuclear shape. The nucleus is bi-lobed in shape (Fig. 1), with a maximum length of 2.33 km. The shape is well constrained by stereo viewing of nearly half the object and for much of the remainder sampled by silhouettes against the light scattered from the coma (Table 1). This bi-lobed shape is crudely similar to that of comet Borrelly (7) but is both relatively and absolutely smoother. The rotation is slow enough that gravity is sufficient to hold the two lobes together for any bulk density of >100 kg m\(^{-3}\).

Constraints on density. The fast (12.3 km s\(^{-1}\)) flyby did not permit determination of the nuclear mass from the spacecraft’s trajectory. The smooth shape of the “waist” region connecting the two lobes might indicate material collecting in a gravitational low, such as observed on asteroid (25143) Itokawa (8). Collection could proceed by in-falling material landing in the gravitational low and/or by in situ fluidization of regolith induced by outflowing gas (9). If some form of frictionless, fluidized flow is responsible for the formation or modification of this region, it should represent a “flat” surface so that it lies along an equipotential with respect to the combined forces of both gravity and rotation. Under these assumptions, which may not be valid, the density of the nucleus can be estimated by fitting potential contours to the observed geometry of the waist (SOM text).

We assumed internal homogeneity, a precession period of 18.34 hours, and a wide range of densities. The variance is minimized for a bulk density of 880 kg m\(^{-3}\) requires modest porosity for pure ice and substantial porosity for plausible rock and ice mixtures.

Any interpretation rests on the character of the surface at the waist, which is mottled on horizontal scales of 10 to 30 m and has some isolated cases of local relief >10 m. The mottling, local topography, and generally gradational boundary distinguishes the waist from the best-observed flow on Tempel 1 (1) and the ponded materials on (433) Eros (10) and Itokawa (8), at least locally, but does not rule out the possibility that the overall shape of the waist is approximately an equipotential. If the surface in this region approaches an equipotential and was formed by flows or by deposition similar to those on other objects, it has subsequently evolved, suffering several meters of erosional etching. These facts suggest that the equipotential assumption may not be reliable and that, unlike the case for Tempel 1 in which a different and more direct approach was possible (11), the density might be considerably higher than deduced under our assumptions.

Geology of surface. The nucleus has two primary terrain types (Fig. 3A): knobby terrain characterized by rounded to angular elevated forms up to 50 m high and 80 m wide and relatively smooth regions occupying both the waist (Fig. 3C) between the two lobes and parts of the larger lobe (Fig. 3B). The elevated forms appear to be the larger members of a population, with most examples near or below our practical mapping resolution (~12 m) (Fig. 3D). The smoother areas have darker central regions, are elongate, and are partially bounded by strings of the elevated forms that make up the knobby terrain. There is marginally resolved mottling of the smooth regions on the larger lobe and better resolved mottling and local topography of 10- to 30-m scale in the waist. The darkest regions of the larger lobe are slightly more sharply bounded than is the darker band within the waist. The elevated forms that constitute the rough terrain are in some areas aligned along boundaries of albedo markings and follow much of the southern edge of the waist. Many of the elevated forms exhibit two to three times higher albedo than the average, which is a much greater range than seen on Tempel 1. Ragged, somewhat sinuous, narrow depressions are visible at high-incidence angles near the southern end, about 10 m deep, up to 90 m wide, and extending for over 250 m.

The average geometric albedo of the nucleus is ~4%. Within the larger lobe area are several roughly equidimensional spots <80 m across that appear even darker than the larger, more elongated “dark” areas mentioned above (Fig. 3E). The darkest unshadowed spots are less than half the average brightness. Although we cannot rule out steep-sided holes for the dark spots near the terminator, they generally occur in regions that are smooth in stereo and show no shadow signatures. Thus, local albedos span at least a factor of 4, compared with <2 on Tempel 1.

Jets occur in all terrains but are clustered in the rough topography of the smaller lobe and mid-to northern part of the larger lobe (Fig. 3). Such clustering of jets has also been seen at comet 1P/Halley (12). At least some jets appear to originate at or near large, bright, elevated forms. Jets also originate beyond the terminator in areas with no direct sunlight, such as along the lower edge of the larger lobe in Fig. 4. Even our resolution of 10 to 12 m is not sufficient to clearly resolve the morphology of the sources of the jets.

This comet lacks a population of depressions, such as those that dominate 81P/Wild 2 (13) or those scattered across Tempel 1 (1, 14). The knobby terrain is similar to some of the rougher areas on Tempel 1. The smoother regions on Hartley 2 do not show the striations that are suggestive of flow markings on the best-observed such region on Tempel 1, and they are more gradationally bounded. The combination of terrains is very different from Tempel 1 or Wild 2, and this comet lacks exposures of thick, internal layers that were prominent on Tempel 1.

Nuclear Activity

CN anomaly. Gaseous CN abundances were measured routinely from the start of observations on 5 September (SOM text). The long-term CN gas production gradually increased from 6 × 10\(^{24}\) s\(^{-1}\) on 5 September to a peak of 3 × 10\(^{25}\) s\(^{-1}\) at perihelion (28 October), after which it decreased again to ~2.4 × 10\(^{25}\) s\(^{-1}\) at closest approach and 1.2 × 10\(^{25}\) s\(^{-1}\) on 25 November (fig. S5). During most of the encounter, the CN production varied periodically with the precession of the nucleus, as did the grains and other gases.
~2 × 10^{31} CN radicals (~800 tons) were released over the peak in dust release [AA] = 10 cm² sr⁻¹ m⁻² W⁻¹, with the duration lasting for many of the chunks. The maximum lifetimes of 10⁴ s for many of the chunks. (November 4)

**Table 1. Properties of Hartley 2’s nucleus.**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>0.82 ± 0.08 km³</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.69 to 2.33 km</td>
</tr>
<tr>
<td>Surface gravity</td>
<td>0.0013 to 0.0033 cm s⁻²</td>
</tr>
<tr>
<td>Precession period</td>
<td>18.34 ± 0.04 hours</td>
</tr>
<tr>
<td>(November 4)</td>
<td></td>
</tr>
<tr>
<td>Geometric albedo</td>
<td>4% (average)</td>
</tr>
<tr>
<td>Mean radius</td>
<td>0.58 ± 0.02 km</td>
</tr>
<tr>
<td>Cross section</td>
<td>0.43 to 1.59 km²</td>
</tr>
<tr>
<td>(Assumed density)</td>
<td>220 kg m⁻³</td>
</tr>
<tr>
<td>Roll period</td>
<td>27.79 or 55.42 ± 0.1 hours</td>
</tr>
</tbody>
</table>

The production of CN also exhibited an anomalous increase, by a factor of ~7, between 9 and 17 September, after which it slowly decreased, returning to the long-term trend line by 24 September (fig. S5). There was a very weak increase in dust release [AA] = 10 cm² sr⁻¹ m⁻² W⁻¹ above its trend in that same period. There was no corresponding increase in water (15). Integrating over the period of 9 to 24 September and subtracting a baseline gas production rate of 7 × 10^{24} s⁻¹, we found that ~2 × 10^{31} CN radicals (~800 tons) were released in the anomaly.

The long-duration, gradual increase and decrease of gaseous emission without a corresponding increase in the dust production is atypical of cometary outbursts, which have sudden onsets and are usually accompanied by considerable dust. The increase is unlike the activity observed at 9P/Tempel 1 or the behavior of any other comet. The spatial profile of CN during the anomaly was very different from that during the rest of the observations and suggests formation of CN from some extended source other than photodissociation of HCN. This could be grains too dark to scatter much sunlight, such as HCN polymers (16) or the CHON grains found at 1P/Halley (17). They would need to be lifted by something abundant and volatile.

**Large chunks.** Radar observations in October showed an ensemble of particles greater than a few centimeters (18, 19). Although clouds of large particles had been reported previously from radar measurements of other comets (20), the location relative to the nucleus and the composition are not known. Previous searches with remote sensing for an icy grain halo in comets had rarely been successful, with the only detections being at large heliocentric distances (21–23).

At EPOXI’s close approach, individual chunks were seen near the nucleus in many images from both MRI and HRI (Fig. 4). The motion of the spacecraft allowed determination of the positions of individual chunks and their motions. A sample of 50 chunks has been followed in many different MRI images and, other than one at 28 km, all were found to be within 15 km of the large end of the nucleus. The motions are all very slow, with 80% moving at <0.5 m s⁻¹ and the fastest moving at <2 m s⁻¹. This implies minimum life times of 10^5 s for many of the chunks.

Escape velocity is poorly defined near the surface because of the rotating, elongated shape as well as the uncertainty in the mass of the nucleus. We estimate that 10 to 20% of the chunks are moving at less than their local escape velocity.

Sizes were estimated from the brightness of the chunks (SOM text). The apparent flux from each of >10⁴ individual chunks ranges from ~10⁻¹⁵ to ≤10⁻¹⁴ W m⁻² μm⁻¹ in the HRI image in Fig. 4, which is similar to that measured in the MRI image taken close in time (Fig. 4). Sampling below 10⁻¹² W m⁻² μm⁻¹ is incomplete. We considered two extreme cases for the scattering properties: icy chunks scattering with the albedo and phase function of Europa (24, 25) and dirty chunks scattering with the albedo and phase function of the nucleus of comet Tempel 1 (26).

The range of measured fluxes corresponds to radii of 10 to 150 cm if they are dirty chunks and 1 to 15 cm if they are ice (nearly pure). Below the minimum size, the chunks blend into the background of unresolved, smaller chunks or grains. Because meter-sized objects are at the extreme of what can be lifted by gas drag and because the smaller, unresolved chunks are demonstrably icy (see below), we argue that the largest chunks are icy and roughly 10 to 20 cm in radius.

The size distribution implied by the fluxes of the discrete chunks is unusually steep. Most of the mass and most of the cross section are in the smallest grains. The discrete chunks contribute roughly 4% of the total surface brightness in the innermost coma (<5 km), and those ≥5 cm (completeness limit) are widely spaced at 4 × 10⁸ m⁻³. If we extrapolate the size distribution (SOM text), >100% of the surface brightness is accounted for just with chunks >0.5 mm. The total cross section of discrete chunks, roughly the same size chunks as ones to which radar is sensitive, is very small as compared with that detected by radar (18, 19), which presumably is detecting much darker chunks over a much larger field of view.

**Heterogeneity of dominant volatiles.** Spectral scans of the comet were obtained from 1 October to 26 November, including several in which the nucleus was spatially resolved. Figure 5 is from a scan 7 min after closest approach, with an MRI image taken at nearly the same time. Red boxes show regions where we have extracted the two spectra shown in Fig. 6, both of which have had the continuum manually removed. The ratio of the H₂O band to the CO₂ band varies spatially by 2.9 times. In these maps (Fig. 5), the emission bands of H₂O and CO₂ are both somewhat optically thick, implying that variations in column density could be larger than in brightness.

The maps show a water vapor–rich region extending roughly perpendicular to the waist of the nucleus and presumably arising from the waist. This region has relatively little CO₂, relatively little gaseous organics, and thus far, no detectable water ice. The region of the jets off the end of the smaller lobe of the nucleus is rich in CO₂ organics, and water ice but has a lower column density of water vapor than above the waist. There is substantial ice in jets emanating from beyond the terminator along the lower edge of the larger lobe of the nucleus. The boundaries and the direct association with the major units of the nucleus seen here are dramatic and suggest very different histories for the waist and the remainder of the nucleus. The coincidence of strong absorption bands of ice with jets that are bright in the continuum suggests that jets are bright when highly reflective ice is present in the jets and conversely, that jets are usually fainter than the nucleus.
because they are of optically thin, relatively dark material. Theoretical calculations of scattering by icy grains (SOM text) show that the predominant scattering grains must be smaller than 10 μm. However, >100% of the surface brightness can be accounted for by extrapolating the chunks to a size of 0.4 mm, implying that the chunks are fluffy aggregates or clusters of ~1-μm solid grains. Either most of the aggregates of order 1 mm have broken up, or they mimic the scattering of the small grains. This result is very similar to the result obtained at Tempel 1 after the impact (no ice was observed before the impact). Those grains were predominantly micrometer-sized (27). The similarity between excavated material from Tempel 1 and ambient outgassing from Hartley 2 suggests that the constituent grains of solid ice are on order of a micrometer in most comets. On the basis of calculations of life times (28–30) for the <10-μm solid components, the ice must be nearly pure for the grains to persist.

The detection of strong absorption by ice, the detection of very large chunks in the coma, the concentration of all species other than H₂O vapor away from the waist of the nucleus, and the relatively smooth surface of the waist lead us to suggest that the material at the waist has been redeposited as a mixture of dirty grains and fluffy, icy aggregates that have not yet sublimed. The warmth of the dirty grains then leads to sublimation of the icy grains just below the surface. We conclude that this aspect of the chemical heterogeneity of the nucleus of Hartley 2 is probably evolutionary.

To determine the absolute abundance ratio, we considered a spectral map made three rotations (55 hours) earlier, when both the precession and roll orientations were the same. Spectra were extracted from 120- and 600-km boxes, both centered on the brightest pixel of thermal emission (a better proxy for the nucleus than a reflected light center). In an aperture of 600 by 600 km centered on the nucleus (fig. S8), and assuming an outflow speed of 0.5 km s⁻¹, we found average production rates Q(H₂O) = 1.0 × 10²⁸ s⁻¹ and Q(CO₂) = 2.0 × 10²⁷ s⁻¹ for ~20% fraction of CO₂. This is higher than the fraction obtained in previous measurements of the global production of CO₂ in this comet (31–33).
the small images of gas.

Fig. 6. Absolute spectra in the coma of Hartley 2 at CA+7 min. The black curve is the water-rich but ice-free spectrum from the box in the H$_2$O vapor panel in Fig. 5, above the waist of the nucleus. The red curve is the ice-rich spectrum from the box in the H$_2$O ice panel in Fig. 5, the jet region near the small end of the nucleus.

Fig. 7. Light curve in visible light compared with the light curve in H$_2$O and CO$_2$. The curve for grains is an expanded version of the box in Fig. 2. The data points for gas are derived from spectral maps. The lower portion shows an expanded view, with images of the CO$_2$ and H$_2$O for each point in the dotted box. The centroid of reflected continuum in each scan has been aligned with the red, horizontal line. Sun is up in the small images of gas.

In Hartley 2, H$_2$O sublimes from the waist with a much lower content of CO$_2$ and barely any trace of icy grains. We tentatively interpret the waist as a secondary deposit of material, although the mechanism of redeposition remains unclear. The most likely mechanism involves fallback of both refractories and icy chunks from the periphery of the active regions. CO$_2$/H$_2$O varies by a factor 2, probably between one end and the other.

From HST measurements (35), CO is <0.3%, implying a ratio of CO$_2$/CO that is >60, which is a far more oxidized environment than is consistent with any model of the outer protoplanetary disk. This is also different from Tempel 1 (~1) (36) and Halley (<1) (37). A large anomaly in CN, too slow to be called an outburst, is unexplained.

References and Notes

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SOM Text
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Table S1
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