

Surface of Young Jupiter Family Comet 81 P/Wild 2: View from the Stardust Spacecraft

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Images taken by the Stardust mission during its flyby of 81P/Wild 2 show the comet to be a 5-kilometer oblate body covered with remarkable topographic features, including unusual circular features that appear to be impact craters. The presence of high-angle slopes shows that the surface is cohesive and self-supporting. The comet does not appear to be a rubble pile, and its rounded shape is not directly consistent with the comet being a fragment of a larger body. The surface is active and yet it retains ancient terrain. Wild 2 appears to be in the early stages of its degradation phase as a small volatile-rich body in the inner solar system.

Jupiter family comets (JFCs) such as 81 P/Wild 2 typically range from the orbit of Jupiter to inner regions of the solar system. These subliming-disintegrating bodies have inner solar system lifetimes that are typically limited to only $\sim 10,000$ years because of the effects of both solar heating and gravity-driven orbital change (1). Although short-lived as JFCs, they are ancient bodies whose history is believed to typically include formation at the edge of the solar nebula, long-term storage beyond the orbit of Neptune, transfer into the inner solar system (< 5 million years ago), and eventual loss by sublimation, disintegration, impact onto the Sun or a planet, or ejection from the solar system (1). On 2 January 2004, the Stardust spacecraft flew 236 km from Wild 2, a body that was captured into a JFC orbit only 30 years ago as the result of a close encounter with Jupiter (2). This flyby provided a brief but intimate view of a body whose surface should contain records of processes that occurred in inner and outer solar system environments separated by a distance of 40 AU and times of billions of years.

Stardust is a sample return mission, and its primary goal is the collection of submillimeter particles for laboratory analysis. As thousands of particles were collected during

the 6.1 km s^{-1} flyby, the mission used its optical navigation camera (3) to take 72 close-up images of the nucleus. These images were taken every 10 s, and exposure times were toggled between 10 and 100 ms to alternate between proper exposure of the comet's surface and faint jet features and to enable the camera to autonomously track the nucleus while moving at maximum rates exceeding 1° s^{-1} . The imaging sequence yielded a series of stereopairs covering a range of solar phase angles from -72° to 103° . The closest image has a minimum image scale of 14 m per pixel.

Shape and size. Wild 2 was found to be oblate, unlike the prolate shapes of the two previously imaged comet nuclei, Halley and Borrelly. The shape can be modeled as a tri-axial ellipsoid having radii of 1.65 by 2.00 by $2.75 \pm 0.05 \text{ km}$ (4). The shortest axis, inferred to be the axis of rotation, has a right ascension of 110° and a declination of -13° . The longest axis, used to define the prime meridian, has an ephemeris position angle of 155° . At kilometer scales, the nucleus is a rounded body, evidence that it is not a collisional fragment of a larger object unless rounding occurs by postcollisional processes. Its prolate ellipsoid shape spinning around the short axis maintains a fairly constant cross section with time, explaining why a rotational light curve has not been detected by ground-based observations. Like other primitive solar system bodies, Wild 2 is dark, and its preliminary geometric albedo was determined to be 0.03 ± 0.015 . An overview of the closest images is shown in Fig. 1, and the naming terminology used by the research team is shown in Fig. 2.

Surface depressions. The surface contains depressions ranging in size up to nearly 2 km across. We distinguish two primary morphologies for circular depressions: pit halo and flat floor. Pit-halo features have a rounded central pit surrounded by an irregu-

lar and rough region of partially excavated material, whereas flat-floor features do not have halo regions and are bounded by steep cliffs. We identified three pit-halo features, of which Rahe (5) is imaged with the best resolution and illumination conditions (Figs. 1 and 3). Rahe consists of a central circular pit 0.5 km in diameter with a rounded bottom and modestly elevated rim. This pit is surrounded by a relatively flat annulus (halo) of excavated material roughly 1.2 km in diameter that is bounded on its outer edge by sharp ragged cliffs up to 200 m in height. Some of the halo regions are at least as deep as the central pit. The halo depression surrounding the central pit is not complete, and there is a $\sim 45^\circ$ sector where the original surface remains, forming a mesa extending to the edge of the central pit.

The second category, flat-floor features, has flat floors encircled by steep, nearly vertical cliffs. Two examples are Left Foot (LF) and a crater 400 m in diameter 2 km west of LF (Fig. 3). Although LF is a double depression feature, it displays the salient features of flat-floor craters. Its northern lobe is 650 m across with a stereometrically measured depth of $\sim 140 \text{ m}$. The walls are nearly vertical ($> 70^\circ$) in places and make sharp contact with the crater floor. There is some rubble at the base of cliffs that is detectable in the highest resolution images. The flat floors seem to be inert at the present time and resistant to sublimation because none of them are detectably associated with observed jets.

Although neither of these two features have raised rims or concentric ejecta aprons, typical hallmark signs for impact, we believe that the pit-halo craters are impact features. They differ from conventional craters, such as those found on asteroids, probably because of two factors: (i) a moderately cohesive target material that is also porous and (ii) extremely low gravity, $\sim 10^{-4} \text{ g}$. A volatile-rich target is potentially important as well, but the effects of volatiles on crater morphology are unknown. A surface composed of cohesive porous material is probably a consequence of the comet being a mix of fine dust and volatiles. Sublimation and the mobilization of volatiles leads to porosity and sintering or other processes that produce moderately bound, rigid materials (6–8).

A possible origin of the pit-halo morphology is that they are the result of impact into

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homogeneous, cohesive and brittle material in a microgravity environment. They may be analogs to typical microcraters seen on lunar rocks (9). The cm size and smaller lunar craters have central, often glass-lined, pits surrounded by ragged regions of spalled and ejected material (Fig. 4). The sector-shaped, unejected region around Rahe is a feature also commonly seen in lunar microcraters. An origin of the excavated annulus by spallation processes does, however, require substantial target strength, which is the reason why we also offer an alternative explanation related to lunar regolith craters some 50 to 100 m across. The regolith craters have central craters surrounded by concentric benches and a raised rim. Experiments (10) demonstrate that such morphologies form in targets characterized by some weak surface layer overlying a more competent substrate. No matter what, both impact formation mechanisms require considerable target strength on Wild 2, at least to depths of some 150 m.

The flat-floored structures resemble the experimentally produced craters in weakly cohesive, porous silicate targets (10). The silicate targets also lack raised rims and produce few ejecta beyond the crater rim. Most of the crater cavity results from the compression of the weakly cohesive, porous target, and this suggests different material motions compared to unconsolidated materials.

We experimentally reproduced the pit-halo and flat-floor craters on the surface of Wild 2 by hypervelocity impacts into resin-coated sand that may be baked at different conditions to produce weakly to strongly bonded materials with porosity between 30 and 40%. Pit-halo structures formed when a loose sand layer covered a somewhat harder substrate, and flat-bottom craters resulted when the unconsolidated surface layer was modestly baked to give it some cohesion: Most disrupted material stayed inside the cavity and formed a flat-floor deposit and steep cliffs formed the rim (Fig. 5).

In hypervelocity impact experiments, including centrifuge experiments up to 600 g , the product of gravitational acceleration (g) and crater diameter (D) shows geometric similarities between experimental and natural structures for any combination of gD as long as the target and projectile material have similar properties (11). A 10-cm laboratory crater at 1 g in a given material morphologically duplicates a 1-km crater in 10^{-4} g . This result implies that the experiments and their dimensional extrapolations seem justified and that the features on Wild 2 are controlled by the strength properties of its surface materials, almost to the exclusion of gravity.

Given the implied cratering history, the lack of both observable ejecta deposits and small craters needs explanation. Most crater volume that is ejected beyond the rim of either a pit halo

or a flat floor may exceed the escape velocity of ~ 1 $m\ s^{-1}$. It is also possible that ejecta, and even landslide materials, are so porous, fine-grained, weak, and charged with volatiles that they disintegrate into fine powder and are blown away by escaping vapor. Most of the small features on Wild 2 are subdued, as if modestly degraded or eroded. There are no unambiguous small impact structures <0.5 km, and their absence may be because of loss via surface erosion or alternatively the impactor population encountered by Wild 2 had an unusually restricted size range, resulting in impact craters >0.5 km.

The comet surface contains depressions <0.5 km that are not circular. Some have

steep walls like the flat-floored craters, whereas others have rounded edges that may have been modified by ablation or the movement of loose materials down the slopes of the depressions. Such irregular depressions have no apparent link to impacts and might be related to sublimation processes.

Some of the largest depressions are complex structures with features that could have formed by impact, sublimation, mass wasting, ablation or a combination of all or some of these processes. The largest depressional features are Right Foot (~ 1 km), Shoemaker basin (1.6 km), Mayo (1.2 km), and Walker (1.2 km). Right Foot is similar to Left Foot, although it is deeper, some of

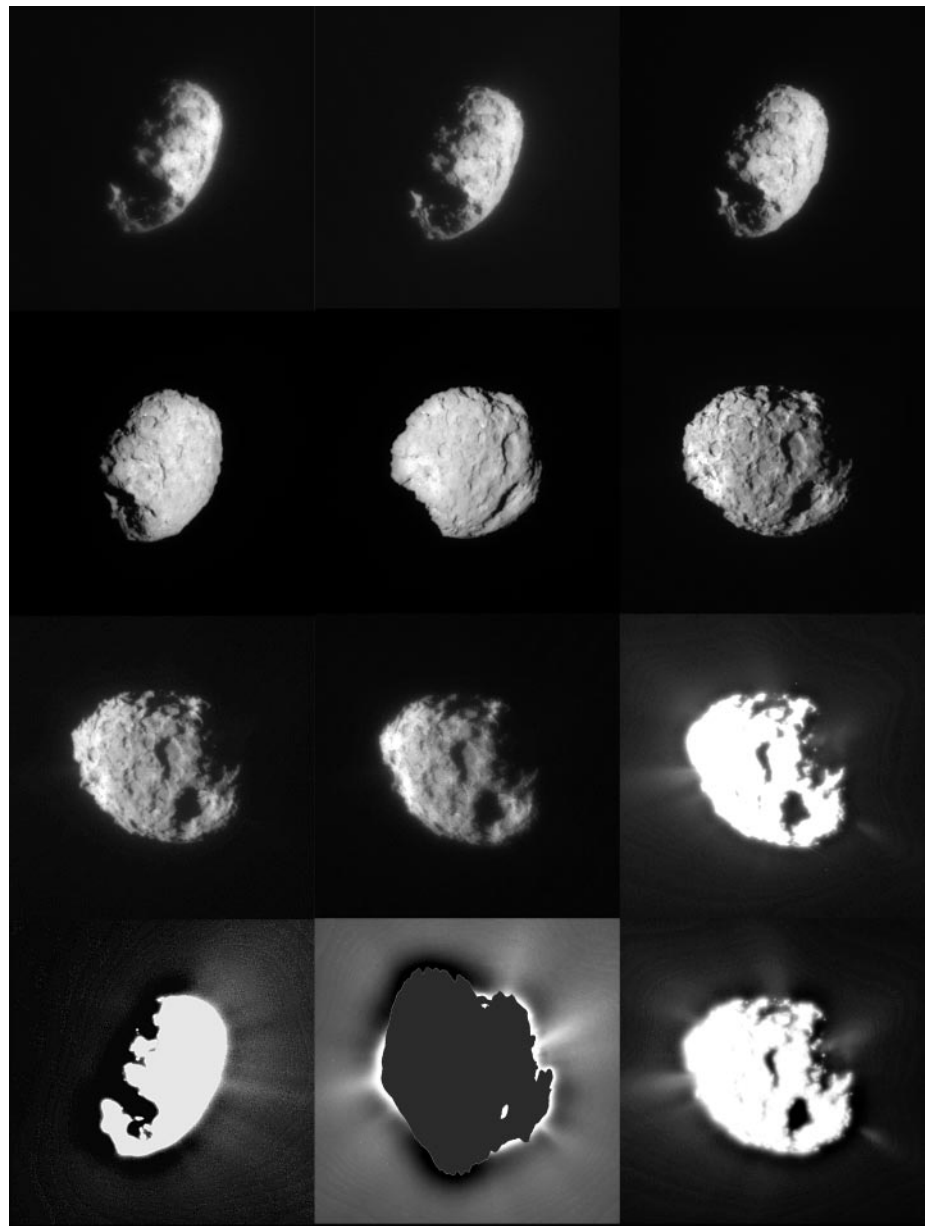
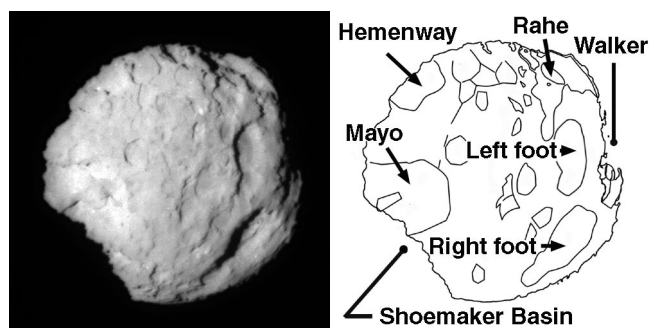


Fig. 1. These 12 images are a good representation of the closest images of Wild 2. The temporal sequence starts at the upper left and continues left to right on the first three rows. The overexposed and out-of-sequence images at the bottom are long exposures taken for autonomous tracking and yield the best jet images. All images were scaled to a constant image scale.

its walls are rounded, and its floor is not as flat and shows considerable fine structure. Shoemaker basin (impact origin is not implied) is an enormous depression on the

west terminator with pinnacles and mesas on its floor (Fig. 3). Mayo has a reasonably flat floor bounded by cliffs that form a highly irregular scalloped perimeter, a 300-

Fig. 2. The closest short-exposure image taken at 11.4° phase angle, the angle between the camera, comet, and the Sun. In the camera-centric directions used in this paper, north is at the top, perpendicular to the ecliptic, and east is to the right. The listed names are those used by the Stardust team to identify features. Basin does not imply an impact origin.



m-by-100-m angular block that is over 50 m high and a strange central feature with fine radial dark lines. Mayo is also a source of several active jets (12), and its irregular form and generally less sharp features, are likely to be related to sublimation. Walker is a depression just at the east terminator that is distinguished by multiple gas jets emanating from its large shadowed interior (12).

Active comets, unlike other solar system bodies, are disintegrating, and they lose a nontrivial fraction of their mass during every orbit. Some of the depressions could largely be formed by sublimation, but it is not clear why sublimation processes, driven by solar illumination on a spinning body, would form globally distributed circular structures. Because comets are so different from other bodies that have been extensively studied, exotic processes must also be considered. For example, it is possible that surface craters could form because of internal explosions, analogous to Earth's steam explosion craters called maars. Internal energy to drive such events could come from phase changes in warming ice, gas confined beneath a nonporous layer, or other scenarios. These energy sources have been discussed as sources of the mysterious but commonly observed cometary outbursts (13, 14). Another exotic but reasonable comet-specific process is fluidization above gas vents, a process that may occur on small scales. If it occurred on large scales, it could levitate materials to form flat-floored deposits. We do not advocate such exotic processes, but they should be kept in consideration.

Other surface features. A major result of the analysis of images of 19/Borrelly taken by the Deep Space 1 mission was the recognition of flat-topped mesas bounded by cliffs (15). It was suggested that these features are remnants of ablation and that gas emission occurs from ablating cliff faces that retreat with time. Wild 2 also has mesas, such as the one touching the south rim of crater Rahe (Fig. 2), but they are much smaller in areal extent than the mesas on Borrelly. As suggested for Borrelly, the plateaus on Wild 2 appear to be cohesive erosional remnants of the oldest least-disturbed cometary surface, and they typically stand ~100 m above local terrain.

The difference in the abundance of mesas on Borrelly and Wild 2 is somewhat perplexing. For a subliming surface, the mesa areal coverage should diminish with time. The larger size and areal coverage of mesas on Borrelly would imply that Borrelly's surface is at an earlier stage of ablation evolution; yet, the presence of sharply defined impact craters on Wild 2 indicate that at least some of its ancient surface is preserved, whereas the lack of craters on Borrelly suggest that the original surface has eroded away in the inner solar

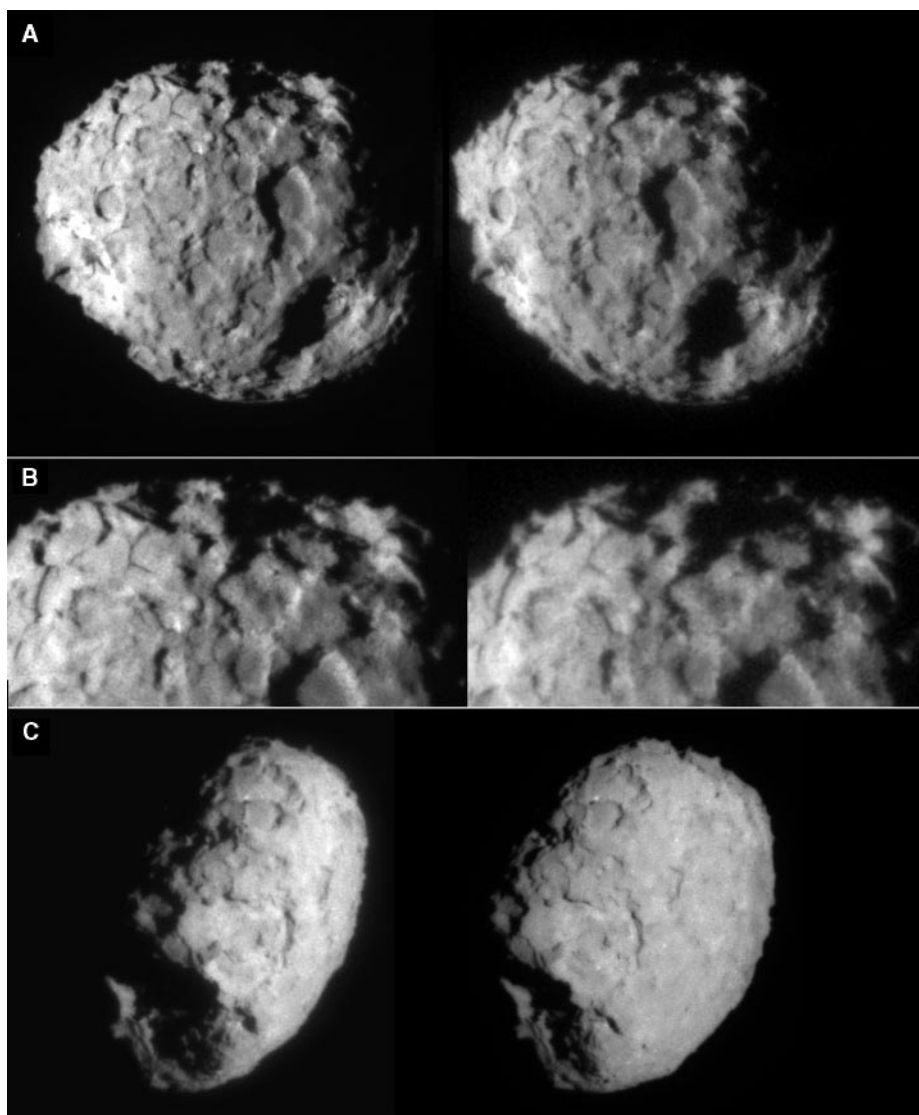


Fig. 3. (A) and (C) images are two stereopairs taken just after and just before closest approach. (B) is an enlargement highlighting the pit-halo crater Rahe, just to the right of center. The bottom pair shows Hemenway (with its bright spot), Mayo, and Shoemaker, all near the terminator. A large pinnacle can be seen in the center of Shoemaker, with its shadow cast on the west wall of the basin. A mesa is also seen on the west limb of Shoemaker. The central region of terminator illustrates the remarkably rugged nature of the surface of Wild 2.

system. Mesas were not apparent in the images of Halley although this might be due to limited resolution (16).

The Right Foot feature shows over 150 m of vertical outcrop on its southeast rim. Modest terracing with layers tens of meters thick seen in this exposure may reflect fine-scale, primary layering of the comet's near-surface strata. The pit halo craters can also be explained by inferring some discontinuity in physical properties at the ~ 100 -m depth level. This evidence suggests that Wild 2 may be stratified at different scales, providing potential clues to its past thermal history.

Lineaments are rare on Wild 2. Fine-scale parallel lines are seen in the west end of the ~ 600 -m irregular depression just southwest of Left Foot and also in Shoemaker (Fig. 3). The most prominent large-scale lineaments are scarps associated with the sizeable region extending from Rahe to and perhaps even including Hemenway. This anomalous area consists of smooth-surfaced semipolygonal areas and small cliffs. The polygonal areas are at slightly different heights and some have upturned edges. The entire region may have been lowered by deflation. The longest feature on Wild 2 is a 2-km-long series of aligned and scalloped scarps that extend from just north of Mayo, through the polygonal slump area, to the northern region of the nucleus just west of Rahe (Fig. 6). At the north end, the feature aligns with an exposed inclined cliff just behind the halo of Rahe. This apparent alignment suggests long-scale, essentially global, continuity and rigidity of the crust of Wild 2. Despite these examples of linear features, the comet seems to lack sizeable, large-scale, deep physical structure. Major structural discontinuities would be reflected in noncircular crater outlines and in the formation of structurally controlled excavation zones and cliff lines. The latter seem to be controlled by local relief, rather than intrinsic structure. This also precludes the presence of substantial lateral heterogeneity caused by the possible juxtaposition of large blocks of physically dissimilar materials that could have been acquired either by the accretion of various planetismals or by extensive collisional processing, resulting in a coarse-grained rubble pile.

There is evidence for down-slope mass movement. Streaks are seen on the northern cliffs of Left Foot, and many cliffs seem to have trace amounts of debris at their bases. Although debris is seen, it is minor and there are no extensive slopes of debris even at the base of the highest cliffs or those that are moderately rounded. Genuine landslides, characterized by flow features, are rarer still, with the best example occurring in the southwest corner of RF. On the basis of these examples, down-slope mass wasting, although present, may not be very significant.

Considering the many steep cliffs, we infer that the cliff formation does not leave behind copious amounts of unconsolidated material. It is possible that cliff debris is weak and fine-grained, so that during movement it disintegrates to dust that is subsequently blown away by escaping volatiles.

Local promontories, termed pinnacles, are apparent on high-resolution images of Wild 2 (Fig. 6). They are ubiquitous but are best seen in regions along the terminator or the limb. This is illustrated by the tall pinnacle in the center of Shoemaker (Fig. 3) that cast its shadow on the west wall of the basin. Pinnacles range from tens of meters to over 100 m in height, and they have varied shapes including spires with pointed tops near the resolution of the images.

Pinnacles were not anticipated land forms on primitive bodies, and their origin on Wild 2 is a mystery. There are several plausible although speculative mechanisms for their formation. Like many terrestrial pinnacles, they are probably erosional remnants created by loss of surrounding material. This process could be assisted by the presence of volatile depleted capping lithology, although the image resolution is not adequate to resolve such details. Pinnacle formation can also occur by erosion of mesas or the erosion of impact ejecta blocks. Small ridges are seen on Wild 2, and isolated pinnacles could form when ridges are thinned by sublimation. The Hemenway region has small ridges that may have been formed by slumping or rotation of blocks. In a few cases, what appear to be pinnacles might be ridges viewed edge-on. If Wild 2 pinnacles are related to surface recession, then the magnitude of surface lost would be comparable to the pinnacle heights, i.e., 100 m or more.

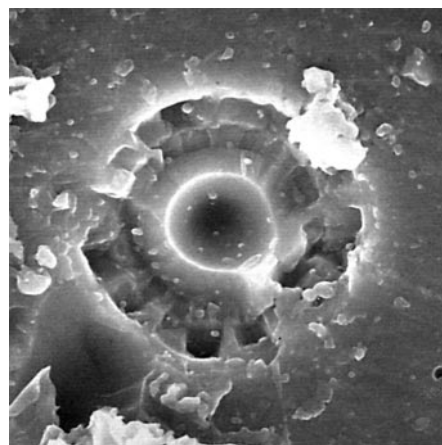


Fig. 4. A 10- μ m-diameter microcrater on lunar glass, showing a smooth central pit surrounded by a spall zone of ejected material. Although much smaller, this crater form, common for centimeter and smaller craters on the Moon, is an intriguing analog to pit-halo craters such as Rahe seen on Wild 2. The pit-halo depressions on Wild 2 formed in a rigid material under microgravity conditions.

A highly speculative but intriguing possibility is that some may be cometary equivalents of hoodoos, upward-pointing spires sometimes seen in eroded volcanic ash. Hoodoo spires are erosion-resistant because they were fumarole conduits and they were hardened by the process. In a comet a somewhat similar, although cryogenic, process could occur in a conduit of escaping water vapor when entrained molecules of moderate volatility freeze out on conduit walls. When the comet surface is eventually eroded by sublimation, the conduit lined with dust and condensates less volatile than water could be resistant and form a pinnacle. If conduits do exist in active comets, this process would not be unreasonable, because gas flow will keep an active conduit near the sublimation temperature of ice and below the condensation point of larger and less volatile molecules.

Overhanging slopes are seen in several locations on Wild 2. The most extreme example is a flap 200 m by ~ 50 m on the north rim of Right Foot that appears to be overhanging in the sequence of stereoviews.



Fig. 5. A 10-cm-sized laboratory hypervelocity impact crater made as an analog of Wild 2's flat-floor craters. The crater was made with a 3.2-mm ceramic projectile impacting a porous target at 2 km s^{-1} .

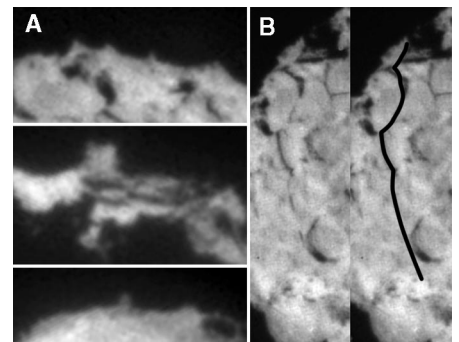


Fig. 6. (A) A variety of small pinnacles and mesas seen on the limb of Wild 2. (B) The location of a 2-km series of aligned scarps that are best seen in the stereoviews.

Whether this flap is impact-related, formed by undercutting or by sublimation, or represents evidence of near surface layering is not clear. The existence of overhangs suggests that the surface may have small-scale layering and further illustrates that the comet's surface is not made of loose material.

As repeatedly observed, the surface of Wild 2 seems to possess some finite strength, and many detailed surface features are characterized by sharp edges and angular shapes. The comet's surface appears crisp and even the bottoms of crevices are sharp and not filled with accumulated debris. There is no evidence for individual ejecta blankets, much less for some global draping by impact comminuted debris or loose materials transported by other process. The comet lacks the subdued landforms that are typical for regolith-covered asteroids. The materials composing the comet surface most likely formed in situ and resemble bedrock.

Albedo features. Full photometric calibration of the images is still under way, and it is premature to discuss the presence of subtle albedo features. The near-zero phase image does show what appear to be subtle but slightly darker regions that are angular and only a few hundred meters in size. If these are real, they could be related to surface processes or perhaps to moderate-scale inhomogeneity in the components that accreted to form Wild 2. We have not yet detected large-scale albedo features like those reported for Borrelly (17, 18), smooth and mottled regimes whose albedo differed by a factor of ~ 3 .

The most significant albedo, or at least brightness, features are rare small bright spots that occur in multiple images at different phase angles. Figure 7 shows a < 50 -m bright spot in the center of Hemenway plains. It is brighter than its surroundings and is seen in different images, ruling out the possibility that it is a phase effect or image artifact. In stereoimages, it has no

height and appears to be an enhanced albedo spot on the surface, but it cannot be ruled out that the feature is not sunlight reflected off a short dust jet. There is an adjacent shadow-like dark spot that could be the shadow of an optically thick jet, but it appears to be the shadow of an adjacent small ridge. Several other bright spots are seen on the comet, some associated with irregular depressions. Whether these brightenings on an otherwise black surface are due to grain-size effects, condensed materials, or other processes is an intriguing question. It is difficult to make a black, primitive, fine-grained, porous material blacker, but brightening can be caused by a number of processes including compaction and deposition of a lighter material.

The bright spots are small and rare, suggesting that they may be short-lived. If they are vents, the albedo increase could be due to condensation of volatiles. After the experience with Borrelly, we expect that most of the illuminated surface is devoid of ice and has a black body temperature near 300 K. On such a hot cometary surface, the coldest illuminated regions will be at active jets, cooled by the outward flow of high pressure gas that is near its condensation temperature and further cooled by expansion.

Mass loss and jets. Wild 2 is an active comet (Fig. 8), ejecting water vapor into space at a rate of $\sim 2 \times 10^{28}$ mol s^{-1} near perihelion (19). The long-exposure images indicate that the full surface of the comet has dozens of regions emitting jets of gas and dust. The width, high collimation, and large number of jets indicate that many of the source regions are small [consistent with Borrelly (20, 21)], probably subsurface, and perhaps short-lived. Wild 2 has a remarkably feature-rich surface, and it is possible that most of the surface has been active at one time or another. As yet, we have not been able to uniquely associate any specific type of

landform as jet sources. Right Foot, the largest feature in the central region of the sunlit face (Fig. 3), is not a source of major jets. Both of the footprint features are near the sunlight pole of the comet (19), and they must be continually illuminated for months on end. If they were major gas sources in the past, they must have been devolatilized or rendered currently inactive.

General mass loss during a single apparition is estimated to amount to only a fraction of a meter averaged over the total surface area of the comet. This suggests that Wild 2 may have lost only a meter or so of surface during its post-1974 history in the inner solar system. Thus, much of the morphologic evidence for mass loss may reside at dimensional scales below our image resolution. However, if pinnacles and other features have ablation origins, then the magnitude of mass loss implied would suggest that Wild 2 had resided within the orbit of Jupiter before 1974. JFCs can alternate from orbits exterior to and interior to Jupiter several times before they are ultimately ejected from the solar system or collide with another body (1).

As suggested for Borrelly (15), cliffs associated with mesa-type plateaus could be favorable sites for mass loss and progressively recess in response to ablation. Although this may be the case, we do not think that the circular nature of most Wild 2 cliffs and the fact that they are holes, not mesas, is compatible with such erosion. Nevertheless, steep cliffs are unquestionably suitable sources for contemporary sublimation processes.

Discussion. The presence of impact craters, active gas, and dust emission shows the juxtaposition of features that are young and old, with the ancient terrain presumably dating back to the comet's residence in the Kuiper belt. Some parts of the ancient surface are resistant to both sublimation

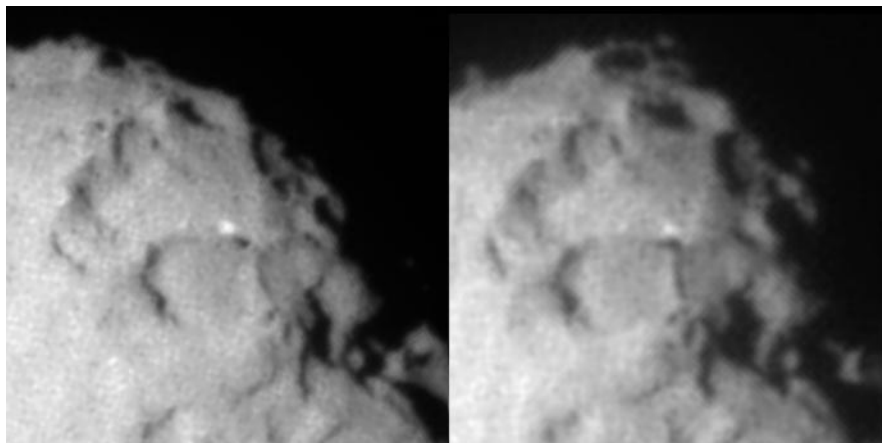


Fig. 7. A stereoview of the bright spot in the central region of Hemenway. A smaller spot barely detected in both images is seen just to the left of the central spot. The stereoimage also shows several remarkable upturned ridges.

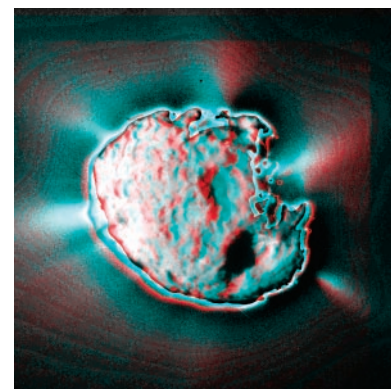


Fig. 8. A stereoanaglyph (magenta on right) of Wild 2 showing the comet and jets seen as sunlight reflected from outward flowing dust and rocks. Unusual jets from the shadowed side can be seen coming from Walker, on the right side of the nucleus, and from a region below Walker.

and obscuration by fallback materials. The presence of large impact craters implies that the cohesive nature of the surface is old and existed before the comet entered the inner parts of the solar system. It is likely to be a weak, porous, and brittle material that surprisingly does not produce debris that forms either talus below cliffs or fallback debris that fills low spots. As a primitive body, it is likely that Wild 2 is a microporous aggregate of very small grains of frozen volatiles and dust. Comets originally formed by the accretion of loose materials and the cohesive nature of materials seen at Wild 2 may have resulted from grain-grain bonds formed, say by trace residues, in sublimation-related processes similar to those observed in the KOSI comet simulation experiments (6, 7). Comets are complex bodies with complex histories,

and there may be multiple opportunities to form cohesive materials even in the Kuiper belt. With its cohesive nature and unusual depression features, the surface of Wild 2 is different from that of asteroids.

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Supporting Online Material

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Movies S1 to S3
Figs. S1 and S2

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RESEARCH ARTICLE

Modeling the Nucleus and Jets of Comet 81P/Wild 2 Based on the Stardust Encounter Data

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We interpret the nucleus properties and jet activity from the Stardust spacecraft imaging and the onboard dust monitoring system data. Triangulation of 20 jets shows that 2 emanate from the nucleus dark side and 16 emanate from sources that are on slopes where the Sun's elevation is greater than predicted from the fitted triaxial ellipsoid. Seven sources, including five in the Mayo depression, coincide with relatively bright surface spots. Fitting the imaged jets, the spikelike temporal distribution of dust impacts indicates that the spacecraft crossed thin, densely populated sheets of particulate ejecta extending from small sources on the rotating nucleus, consistent with an emission cone model.

Cometary activity is characterized by solar energy-driven sublimation of water ice and other volatile substances from the nucleus into the coma, while refractory material (dust particles of various sizes) is dragged along. Jets emanating from isolated emission centers on the nucleus appear to be the primary source of cometary activity (1–5).

The comet Wild 2 data, collected by the experiments onboard the Stardust

spacecraft during its encounter with the comet, include images of jets and the spikelike temporal distribution of dust particle impacts. To interpret the data, we applied a conceptual model of an emission cone (6). This model affirms that a highly collimated column of dust particles, which are ejected continuously (or quasi-continuously) from a small active source on a rotating nucleus, populate a thin conical sheet (or a part of it, if activity is interrupted during a diurnal cycle) in the coma before the formation is gradually dispersed by various forces.

The nucleus and its rotation. Of the three specific Wild 2 models the parameters of which are listed in (7), the effective nucleus diameter of 4.0 km, predicted from the high-density model, is most consistent with the results derived from the Stardust data (Table 1), suggesting that the average geometric albedo of the nucleus is

probably close to 4% in the Cousins R band (wavelength range of 550 to 900 nm). The model indicated the presence of two active regions on the nucleus: Source I, near the rotation pole that was sunlit around the 1997 perihelion; and Source II, on the other polar hemisphere, about 25° from the equatorial plane. The model predicted that during the Stardust encounter only Source II would be active. The outgassing area of this source was estimated at 9.5 km² or nearly 20% of the nucleus surface. In the absence of time-lapse imaging (8), the model could provide no information about the nucleus rotation period or the longitudes of the sources.

The orientation of the comet's spin vector presents an intriguing problem. Of the three results independently derived from the jet morphology in 1997 (7, 9, 10) (Table 1), the two consistent ones suggest an obliquity, *I*, of 75° to 80°. The result (9) is particularly notable, because it is derived by modeling the jet profiles with the use of an algorithm for extended sources. In contrast, fitting a triaxial ellipsoid to the nucleus figure in the images taken during the Stardust encounter yields an obliquity of 55° to 57° (Table 1). At this spin-axis orientation, Source II (especially given its large extent) should have been active, but was not detected in late 1996, more than four months before perihelion. Although the rotation models 1, 2, 4, and 5

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