News & views

Astronomy

The eye of the skull and a tale of a comet

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The Philae spacecraft was meant to anchor itself to the surface of the comet 67P/Churyumov–Gerasimenko, but instead bounced into a hidden grotto. The telltale markings of its passage reveal details of the comet's fragile boulders. **See p.697**

Astronomers are often like the proverbial blind men touching an elephant: one holds the tusk and thinks it's a bull; another grabs the tail and decides it's a horse; and a third feels the trunk and says it's a snake. Humans rarely get to touch anything in space — so far, only the Moon. Robotic landers and probes have extended our reach to the surfaces of Mars, Venus, Titan and a handful of asteroids and comets, but in each case they have yet to reveal the whole 'animal'. This is especially true of comets, the denizens of the outer Solar System that sometimes make close approaches to the Sun, and whose progenitors contributed to the inventory of organic and volatile compounds in early Earth[1].

The unplanned spacecraft experiment reported by O'Rourke *et al.*[2] on page 697 is therefore of particular importance. The authors present a detailed reconstruction of what happened on 12 November 2014 after the Rosetta spacecraft deployed the Philae lander to the surface of comet 67P/Churyumov–Gerasimenko. Philae did not stick the landing, as they say in gymnastics, and this misadventure provided a unique opportunity for icy boulders on the comet to be studied.

Most planets and the largest moons have a gravity field comparable to Earth's, so we can make headway in understanding their geological behaviour. But minor bodies — asteroids, comets and small moons — are in a class of their own. For example, common asteroids only a few hundred metres in diameter seem to be piles of rubble held loosely together by gravity. They are not zero-gravity environments (there is a 'down'), but ground movements of only tens of centimetres per second, caused by impacts or the digging of a lander, for example, will send surface rocks into escaping orbits. Our lack of predictive knowledge about this alien geology makes minor bodies dangerous for landers.

Sample-return missions — in which material is collected from an extraterrestrial object and brought back to Earth — have been successful for small asteroids. These missions have used long booms in brief 'touch-and-go' procedures to minimize the uncertain, potentially dangerous interactions between the spacecraft and the surface. This approach was used by the Japan Aerospace Exploration Agency's Hayabusa missions[3] to two small asteroids in 2005 and 2019, and more recently by NASA's OSIRIS-REx mission[4], which was deployed to sample the asteroid Bennu on 20 October 2020 (see *Nature* **586**, 484–485; 2020). Piece by piece, we are starting to understand asteroids.

Comets are more complex mission targets. They are dust-rich bodies cemented together by frozen volatile compounds (mainly water and carbon dioxide). Most cometary bodies reside in their native habitat far beyond Neptune, where they have been in cold storage since before the planets finished forming. Occasionally, one is diverted to the inner Solar System, where it can make an astronomical spectacle and, in principle, can be sampled in the way that asteroids have been.

The icy masses of these comets sublimate away each time their orbit brings them close to the Sun, forming deposits known as lags,

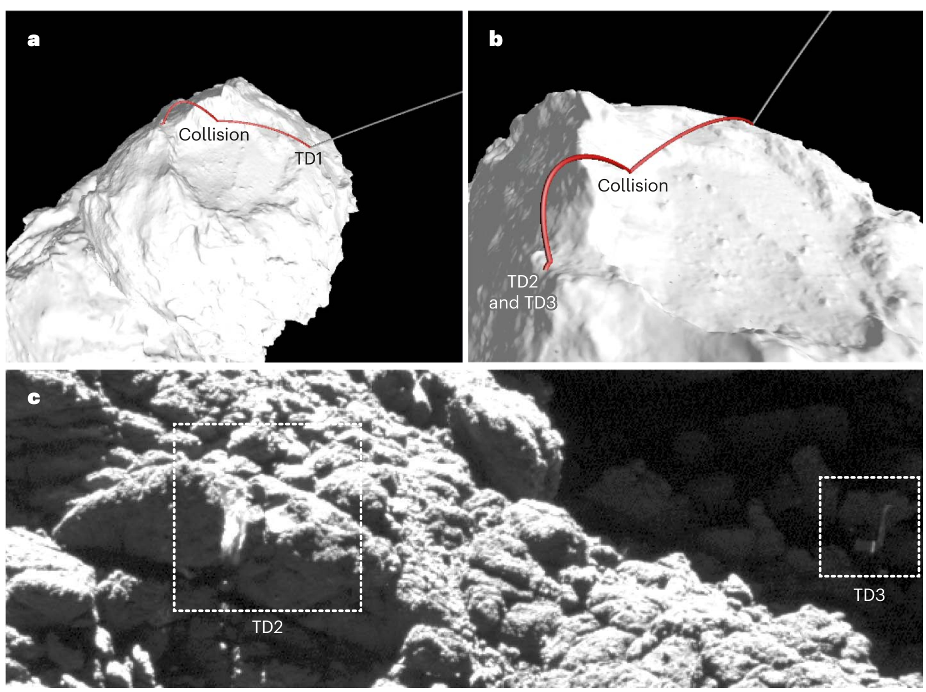

Figure 1 | The flight of the Philae lander. a, b, On 12 November 2014, the Philae spacecraft was dispatched to the surface of the comet 67P/Churyumov–Gerasimenko, but the landing didn't go to plan. Philae briefly touched down at its target location (TD1), but rebounded into a low-arc trajectory. After undergoing a glancing collision with one edge of the comet, it touched down briefly again at another site (TD2). Finally, it bounced into a dark grotto (TD3), where it came to rest. The comet shown here is a computational model of 67P/Churyumov–Gerasimenko. **c**, O'Rourke *et al.*[2] now report that the location TD2 is close to TD3, and that Philae left a skull-like imprint (left of centre in the box for TD2) when it bashed between some massive boulders. Part of Philae can be seen faintly in the box that indicates TD3. The box for TD3 is approximately 5 metres in width. (Images from ref. 2.)

and producing irradiated residues. They have some of the most irregular topography in the Solar System, and are subject to unpredictable outbursts of material. The acquisition of samples from the surface of a comet remains a top priority for cosmochemists searching for diagnostic signatures of the origin of planetary water[5] and for prebiotic chemicals[6] such as amino acids and phosphorus. Such samples would also help constrain physical models and the chronology of planet formation and its relationship to stars.

Sample-return missions have so far visited near-Earth asteroids on orbits that can be attained with minimal propulsion. Reaching a comet takes a lot more effort. The Rosetta mission[7] required four gravity assists — manoeuvres in which the gravitational pull of a planet is used to speed up a spacecraft — before it could match the orbit of comet 67P. Moreover, a surface sample-return mission would have to make the journey to the comet and then back home, which has not yet been attempted. Sampling is further complicated by the fact that the pristine cometary material preserved from the early Solar System is buried beneath an accumulating rind of altered and recrystallized material, produced as the comet fritters away.

The Philae lander's goal was the next-best thing to sample return: to land on and analyse the comet's solid surface, conduct visual, tactile and remote-sensing experiments, and send the data back to Earth[8]. Unfortunately, the landing did not go to plan. The harpoon and thruster system that was meant to anchor Philae to the surface failed to deploy, so instead of landing, the spacecraft touched down only briefly before rebounding (Fig. 1a), leaving a crater-like imprint where it made initial contact[9]. It then entered a long-arc trajectory, underwent a glancing collision with a ridge, and touched down briefly again (Fig. 1b). Finally, it bounced into a dark grotto where it came to rest, running out of power in two days.

Before its untimely end, Philae achieved some notable scientific goals, including the first radar transmission through a comet nucleus[10]. It also attempted a drilling experiment, which, if the readings are correct, indicates that the surface is as hard as weak sandstone (the compressive strength was 2–4 megapascals; ref. 11). This is much greater than the strength that was estimated by an analysis of the landing imprint[9] (several kilopascals, which is comparable to the strength of lunar soils).

The 900-metre cliff in the Hathor region of 67P demonstrates that the comet can support large structures. However, this cliff bears less 'weight' than an approximately 2-cm ridge on Earth, where gravity is about 50,000 times greater; a strength of 100 Pa, similar to that of powdery soil, would support it. The comet's overall shape — that of two attached spheroids, a bit like a rubber duck — suggests that it formed from the gentle collision of two rubble piles[12]. With various estimates and measurements of its strength coming up with different answers, 67P is very much the elephant.

The flat regions of a comet nucleus are safest for spacecraft landing operations, but can be covered by lag to a depth of many metres. This might explain the lunar-like compressive strength at the initial touchdown site. Thus, a silver lining to Philae's bumpy passage and eventual demise is that, as it crashed around in the rough terrain, it made dents in the comet's blockier materials, thereby performing experiments that no rational mission engineer would propose. If these crash sites could be identified in images taken by the Rosetta orbiter, the impacted material could be analysed to determine its physical response to having a 100-kilogram, cubic-metre-sized spacecraft crash into it, as O'Rourke *et al.* relate.

The location of Philae's first touchdown site (TD1) was identified in Rosetta images early in the mission, but the lander was not discovered in its grotto (Fig. 1c) until near the mission's end, two years later. This led to attempts to reconstruct Philae's two-hour journey and search for surface markings. O'Rourke *et al.* now report the location of the second touchdown site (TD2), and reconstruct what happened there. They compare images from both spacecraft, and data from Philae's accelerometers and magnetometer, to show that Philae left a distinct imprint near a feature that the authors call skull-top ridge after its distinctive shape (Fig. 1c), where the lander bashed between some massive icy boulders.

"The authors estimate the compressive strength of ice in the comet's boulders to be similar to that of fresh snow."

I was originally sceptical that the authors' reconstruction could be so precisely defined, but in the end found their analysis to be compelling. The fact that the spacecraft struck some boulders is noteworthy, because one can argue that large boulders are 'fresh' comet material — unlike the surface at TD1, which was selected for lander safety. According to O'Rourke and co-workers, the 'eye' of the skull was made when Philae formed a dent about 25 cm deep in the boulder ice, before rebounding. The authors estimate the compressive strength of the ice to be less than 12 Pa, on the basis of the reconstructed impact and rebound velocities. This value is similar to that of fresh snow, and is consistent with the Rosetta–Philae radar experiments, which suggest that the comet's interior is extremely porous[10].

O'Rourke *et al.* might have tweaked as much information as is possible from their forensic exercise. Their analysis provides a key measure of how some comet materials respond to the momentum of a massive spacecraft — they're evidently soft and crushable. Moreover, the 'eye' is much brighter than the material around it, suggesting that Philae broke through a thin, dark layer to expose pristine nucleus material.

Does this mean that sampling a comet nucleus will be easy? Hardly. This is not the first misadventure to occur on the surface of a small planetary body, nor will it be the last. But O'Rourke and colleagues' engineering-level analysis of Philae's tumultuous landing helps set boundaries for the operational parameters of future missions, reducing their uncertainties. Unfortunately, the findings also suggest that the best places to sample comets will not be the flat plains, but along the newly exposed ridges, cliffs and boulder piles, which are more difficult to land on.

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