News & views

Planetary science

Surprise ocean prompts update of rules for moons

Matija Ćuk & Alyssa Rose Rhoden

The shifting orbit of one of Saturn's moons indicates that the satellite has a subsurface ocean, contradicting theories that its interior is entirely solid. The finding calls for a fresh take on what constitutes an ocean moon. **See p.280**

The detection of liquid water oceans under the icy surfaces of outer Solar System moons suggests that these moons could provide abodes for life under conditions that differ markedly from those on Earth. However, it can be a challenge to detect subsurface oceans directly, so inferences about candidate ocean moons are typically drawn from comparison to moons known to harbour oceans, such as Jupiter's Europa and Saturn's Enceladus. These moons have many similarities in terms of both the conditions that sustain their oceans and the way that their surfaces indicate the existence of an internal ocean. If the criteria were set by these moons, the small Saturnian moon Mimas would easily be ruled out as an ocean moon. It therefore comes as a surprise to learn that Mimas must have an internal ocean, according to results reported by Lainey *et al.*[1] on page 280.

Mimas is a small body whose most distinctive feature is a crater so large that it gives the moon the appearance of the Death Star space station from the Star Wars franchise. It has a slightly egg-shaped form, which is common among planetary satellites that are in synchronous rotation (that is, those that keep the same side facing the parent planet). Identifying Mimas's stealth ocean required Lainey *et al.* to analyse precise measurements of changes in the moon's orbit and rotation, which are affected by the make-up of its interior. These changes can be tracked by measuring the moon's moments of inertia, which measure its resistance to rotational acceleration, and depend on both the moon's surface shape and how matter is distributed inside it.

Mimas's moments of inertia were previously probed[2] by looking at rocking motions, known as librations, that the moon makes as it is tugged by Saturn's gravity. These measurements revealed that Mimas's librations are much larger than would be expected from the shape of its surface. This could be explained by the moon having either a very elongated rocky core, which would enhance the difference between its moments of inertia, or an internal ocean, which would allow its outer shell to oscillate independently of its core. Because there was no other widely recognized evidence for an ocean, many planetary scientists preferred the elongated-core hypothesis. But the once-neglected – and just as plausible – ocean option[2] now has support from another corner.

Moments of inertia can also be used to quantify a moon's gravity field, which acts on the parent planet and on other bodies. An oblate (slightly flattened) body such as Earth or Saturn makes the orbits of its satellites precess forwards, meaning that the ellipses traced by the orbits rotate slowly in space, in the direction of the satellites' (much faster) orbital motion. Intriguingly, the elongated shape of a moon in synchronous rotation induces the opposite effect: the mutual orbit of the moon and the planet precesses backwards, opposite to the direction of orbital motion.

By analysing measurements of the position of Mimas made by NASA's Cassini spacecraft, Lainey *et al.* concluded that the moon precesses backwards in this way (Fig. 1) – a tendency that must result from the elongation of its own gravity field. The big surprise is that, if Mimas is assumed to be frozen, the moments of inertia calculated from its librations do not match those required to explain its orbital precession. In fact, Lainey *et al.* showed that no internal distribution of mass in a solid body can explain these two data sets. The only viable conclusion is that Mimas has a subsurface ocean.

There are many implications of Mimas being an ocean world. For starters, Mimas has a large orbital eccentricity, which means that its orbit

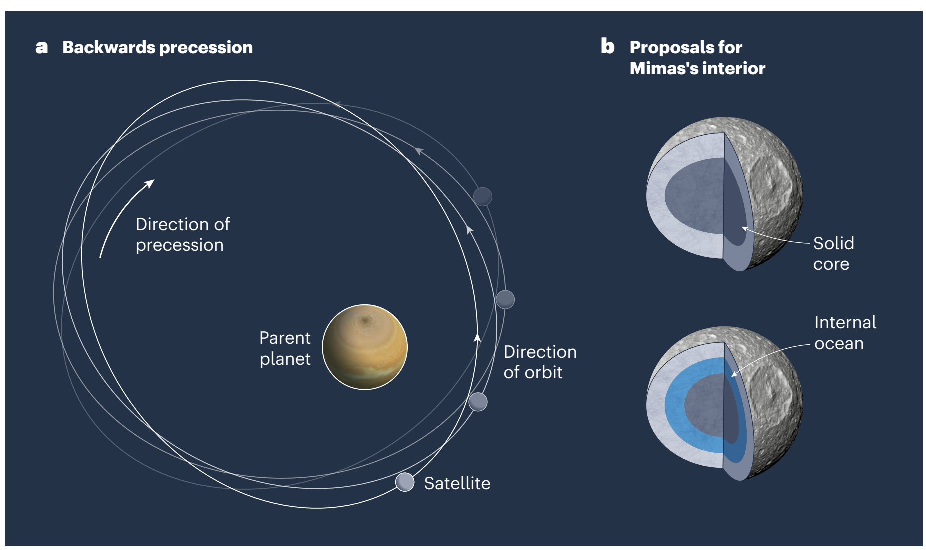

Figure 1 | Evidence for a subsurface ocean. **a**, The orbits of some satellites can precess backwards, meaning that the orbital path rotates slowly in a direction opposite to that of the satellite's orbit around its parent planet. **b**, Lainey *et al.*[1] detected a small amount of backwards precession in the orbit of Mimas, one of Saturn's moons, after removing other dynamical effects. The authors showed that this precession isn't consistent with predictions that assume that Mimas is fully solid. The authors' finding settles a debate about whether the moon's interior comprises a very elongated rocky core or an interior ocean. Lainey *et al.* showed that no internal distribution of mass in a solid body can explain the existing data, and so conclude that Mimas must have a subsurface ocean.

traces an ellipse rather than a perfect circle. But this eccentricity would rapidly diminish if the moon's interior could readily respond to gravitational forces exerted on Mimas by other bodies. This indicates that the ocean or the orbital eccentricity – or even both – must have been around for only a short time, of the order of tens of millions of years.

A young ocean also matches constraints derived from Mimas's geology; in particular, the large crater, known as Herschel, could not have formed in an ice shell that is as thin as Lainey and colleagues (and others[2]) predict. Rather, the ice shell must have thinned by tens of kilometres since Herschel formed[3]. A thinning ice shell might also explain why Mimas lacks the heavy fracturing observed on ocean moons such as Europa and Enceladus[4]. In this way, geological features can help researchers to pin down the timing of ocean formation and the orbital conditions that stimulated the growth of an ocean.

The idea that Mimas's ocean could have formed relatively recently also has implications for other features of the Saturnian system that remain mysteries, in spite of clues retrieved by the Cassini mission. Saturn's bright icy rings are apparently young in geological terms[5], but not all scientists agree[6]. The heavily cratered icy moons seem ancient, but the source of the bodies that made the craters is disputed[7,8], and there are suggestions that the moons themselves are also geologically young[9]. The clues provided by Mimas and its ocean could help to resolve some of these conundrums.

Finally, adding Mimas to the catalogue of ocean worlds changes the general picture of what these moons can look like. The idea that relatively small, icy moons can harbour young oceans is inspiring, as is the possibility that transformational processes have occurred even in the most recent history of these moons. Lainey and colleagues' findings will motivate a thorough examination of mid-sized icy moons throughout the Solar System. Most notably, there is a suite of mid-sized icy moons orbiting Uranus, which was selected as the highest-priority target of a NASA flagship mission by the Planetary Science and Astrobiology Decadal Survey.

Mimas also has an important lesson to teach scientists: intuition is excellent for generating hypotheses, but not sufficient for drawing conclusions. The Solar System will always have surprises in store, and researchers must be open enough to new ideas and unexpected possibilities to recognize them.

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Archaeology

Ancient toolmakers in north Europe identified

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DNA analyses of skeletal fragments from a site in Germany provide evidence that humans, rather than Neanderthals, were responsible for a particular stone-tool industry called the Lincombian–Ranisian–Jerzmanowician. **See p.341**

Analyses of stone tools and human skeletal remains can help to determine whether specific excavated levels at archaeological sites are associated with Neanderthals or anatomically modern humans (with a body form similar to ours) during the period when both groups were present in Europe. Mylopotamitaki *et al.*[1], on page 341, and Pederzani *et al.*[2] and Smith *et al.*[3], writing in *Nature Ecology & Evolution,* report their analyses of Ilsenhöhle, an archaeological site from this period near Ranis, Germany. The findings shed light on the environmental conditions there and identify the inhabitants linked to a widespread stone-tool industry in the region, for which the associated population was previously unknown.

The arrival of anatomically modern humans in Europe has long been of interest to scientists because this migration did not take place in a previously uninhabited landscape. Neanderthals (*Homo neanderthalensis*) with their classic anatomical form occupied Europe from at least 200,000 years ago[4] and were related to individuals who had a subset of Neanderthal anatomical features and were present in Europe by approximately 400,000 years ago. *Homo sapiens* arrived in southeastern Europe by 46,000 years ago[5]. Neanderthals subsequently disappeared, leaving only *H. sapiens*. The reason why Neanderthals were replaced by humans is the source of often-heated debate. To understand the factors in this population replacement, termed the Middle to Upper Palaeolithic (MUP) transition, we must learn exactly when *H. sapiens* arrived in Europe and for how long the two populations occupied the landscape.

Mylopotamitaki and colleagues used a protein-analysis technique (a proteomic method) to determine that the remains of individuals found at Ilsenhöhle (Fig. 1) were hominins (members of the genus *Homo*, which includes humans and close relatives). The authors also analysed DNA from mitochondrial organelles to demonstrate that these individuals were *H. sapiens*, and carried out statistical analyses of radiocarbon-dating evidence to show that the remains are approximately 45,000 years old. Studies by Pederzani *et al.* and Smith *et al.* provide a window into the environmental conditions at the site during its occupation, reveal the ecology of the recovered prey species and offer insights into how the human groups that frequented Ilsenhöhle incorporated this site into their use of the region.

Archaeologists have defined a number of regionally specific stone-tool technological traditions for the MUP transition, but skeletal remains in association with these industries are sparse, and most sites have contextual problems – the archaeological relationships between the few remains and the MUP transitional stone tools with which they are associated are difficult to determine. As a result, it is unclear who created these technologies, but working this out is essential to infer the cultural dynamics of populations of late Neanderthals and early modern humans in Europe and to determine whether interactions between these groups, which are known to have occurred[6], might have influenced the technologies and objects used by a culture. Two archaeological levels excavated by Mylopotamitaki and colleagues at Ilsenhöhle are associated with one of these MUP transitional industries, termed the Lincombian–Ranisian–Jerzmanowician (LRJ).

Mylopotamitaki *et al.* demonstrate that the LRJ-associated levels are clearly separated