PERSPECTIVES: PLANETARY SCIENCE

Probing Europa's Third Dimension

Clark R. Chapman

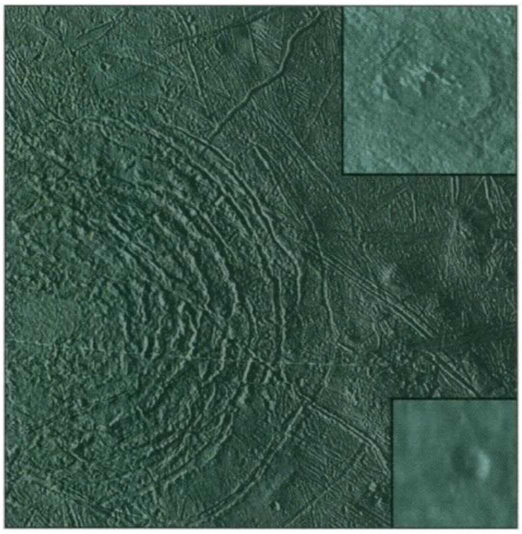
Jupiter's moon Europa may harbor an ocean more voluminous than the total oceanic water on Earth beneath its icy surface. It could be an abode for life located much farther from the sun than the classical "habitable zone" near Earth's distance from the sun. Reasons for Europa's warmth were explained (*1*) during the era of Voyager fly-bys of Jupiter. Jupiter's immense gravity, mediated by resonant gravitational interactions among Io, Europa, and Ganymede, generates tidal forces that dissipate heat within each satellite, especially Io, which releases heat through continuously erupting volcanoes.

About 1.6 times as far from Jupiter as Io, Europa is heated less. Voyager images of its unusually flat, nearly crater-free surface fueled speculation about an ocean. Now the Galileo mission to Jupiter is in the middle of its final, two-year-long, Europa-intensive extended phase. Galileo gravity field data (*2*) show that Europa's H_2O layer (whether liquid or ice) averages 80 to 170 km in thickness. That some of it might be liquid is implied by Galileo magnetometer data (*3*), which indicate magnetic fields due to induced electrical eddy currents within a near-surface conducting medium more than 10 km thick—perhaps a briny ocean.

The most seductive evidence for a Europan ocean was the Galileo images of the region called Conamara Chaos, released with great fanfare in April 1997. They show multikilometer-long ice rafts seemingly floating in a refrozen matrix. After a year and a half of further imaging and analysis, Galileo scientists have presented more sober interpretations of Europa's landforms (*4*).

How does one tell from the surface of an object what lies beneath? What tastes and textures are revealed about an exotic fruit by its skin? Planetary geologists struggle to infer the third dimension from what, in Europa's case, is topography almost as flat as Kansas: mostly lengthy, double ridges that are rarely higher than a couple of hundred meters. Few explanations for the variety of intricate ridges seem fully satisfactory (*4*).

Circular features, the simplest of landforms, may hold the most direct clues about Europa's subsurface. Landscapes of most planets and moons are dominated by circular, concave craters. Before the Apollo missions, debates raged about whether lunar craters were of impact or volcanic origin. Nature loves circular shapes (such as the pits in a baking pancake), so we should not be surprised that the eventual answer was both impact and volcanic; indeed, many smaller lunar craters may have a third origin, collapse of regolith soil into subsurface cavities (*5*). Of course, primary impact craters caused by comets and asteroids and so-called secondary craters, formed by reimpact of material ejected from primary craters, overwhelmingly dominate on the moon and other bodies.



Lasting impact. Galileo images of craters on Jupiter's moon Europa. The ring structure Tyre is about 125 km across. Pwyll (top right) is a recent but flattened 26-km impact crater at the center of an extensive system of bright radial rays. A smaller 10-km crater has more normal impact crater morphology (bottom right).

Thus, the ~10-km-diameter circular cavities in Europa's surface, detected near the resolution limit of Voyager's best images and in Galileo's first 1996 images, were assumed to be impact craters as well. Astrogeologist Gene Shoemaker, who had been making a telescopic census of small comets near Jupiter, determined from the apparent crater density and dividing by his comet flux that Europa's surface was about a billion years old (*6*). But later Galileo close-ups of Europa revealed a dearth of impact craters; the ostensible craters on earlier pictures turn out to be of internal origin (see discussion below). Primary impact craters are actually rare on Europa. Less than a month before he died in an auto crash while surveying Australian impact craters, Shoemaker concurred that the later pictures, combined with his impact flux, implied that Europa's surface averages only about 10 million years old.

The few impact craters on Europa tell us about the depth to the water (or is it a slurry or just very warm ice?). The shapes of Europan craters change drastically with size (see figure). Impact craters smaller than 20 km in diameter look like the relatively deep, bowl-shaped smaller impact craters on other solid-surfaced worlds. Somewhat larger craters, such as Pwyll (26-km diameter), show classic impact features (a central peak and slumped walls) but are exceedingly flat. Still larger impacts yielded no craters at all but instead generated large concentric ring structures, exemplified by Tyre.

Supported by hydrocode modeling of impact into a brittle layer overlying a fluid, Moore *et al.* (*7*) argue that crater morphologies on Europa can be explained if Europa's ice crust is 10 to 15 km thick. Small impacts form traditional bowl-shaped craters in the hard ice. Impacts that would have formed craters exceeding 30-km diameter instead punched through the ice, yielding ring-fractured structures tinted by the apparently reddish color of fluid materials derived from beneath the ice. Abundant secondary craters surround these ring structures, proving their impact origin. The transitional-sized Pwyll is flat and reddish, suggesting that the transient cavity during crater excavation tapped into the ocean, yet the ice was thick enough to form—if not sustain for long—the familiar features of an impact crater.

What about those abundant nonimpact circular features, the various collapse pits, spots, moats, and domes that are especially common in tropical latitudes and often of reddish color, suggesting derivation from below? Their characteristic sizes and spacings (5 to 20 km), plausibly resulting from a diapiric (*8*) mode of solid-state convection of warmer ice beneath a cold, brittle ice lid (*9*), also imply a thickness of the total convecting ice crust of about 10 km. Coalescing diapirs in especially active re-

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gions may form the larger, irregularly shaped, broken ice-raft terrains called "chaos."

Water may once have been near Europa's surface in chaos and in some rare, circular, pondlike regions. The search for thinner-than-average crustal localities, which may permit future technological penetration to the putative ocean, should concentrate on incipient circular features of internal origin. Whether what underlies the ice is, in fact, a briny ocean or a more viscous slurry remains to be proven.

References and Notes

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PERSPECTIVES: NEUROSCIENCE

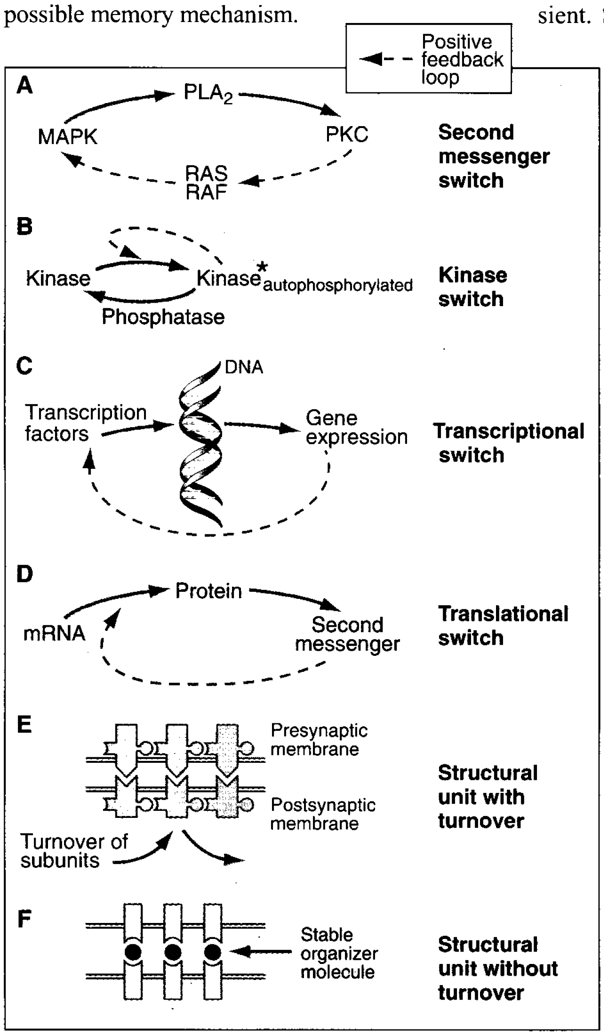
What Maintains Memories?

John E. Lisman and Justin R. Fallon

After we switch on the room lights, we would surely be surprised if the light switch spontaneously turned off. Light switches are designed to remember what we tell them, and they rarely forget. Digital computers elaborate on this principle by using large arrays of binary switches to store information of all kinds. In biological systems there is a similar need to store information. Indeed, a central unsolved problem is to elucidate how memories are stored in the brain.

It is generally thought that electrical activity in neurons leads to long-lasting changes in the strength of synapses and that it is these changes that store memories. But how does the synapse remember whether it is strong or weak? Some type of stable switches must be involved, but the principle by which stability is achieved remains elusive. Several ideas have been proposed, and another intriguing one is put forward on page 381 of this issue by Bhalla and Iyengar (*1*) (see the figure).

Bhalla and Iyengar propose a switch that operates through a positive feedback loop consisting of a cascade of biochemical reactions. Bhalla and Iyengar point to evidence that MAPK can activate protein kinase C (PKC) (through phospholipase A_2). But the reverse is also true: PKC can activate mitogen-activated protein kinase (MAPK) (through Raf and MEK). Clearly there is the potential for positive feedback (see part A of the figure). The authors have used computer simulations to show that this biochemical loop can be bistable. If the enzymes are only weakly activated by an external stimulus, MAPK activity increases, but returns to baseline after the stimulus is removed. With stronger stimulation, the positive feedback becomes strong, and MAPK activity can be sustained in an "on" state long after the stimulus is removed, perhaps indefinitely. This biochemical loop can thus act as a bistable switch and is a possible memory mechanism.



The substance of memories. Molecular mechanisms that can result in stable changes at the synapse, and so are candidates for memory storage devices.

Indeed there is increasing evidence for a role of MAPK in long-term potentiation (LTP) in the CA1 region of the hippocampus, the standard model system for associative synaptic modification. Inhibitors of MAPK block the induction of LTP, and biochemical assays show that the kinase becomes activated. But the available evidence argues that this kinase is not the mechanism by which LTP is maintained. First, the activation of MAPK is only transient. Second, if an inhibitor of this kinase is applied *after* LTP induction, the inhibitor has no effect on the maintenance of LTP (*1*, *2*).

Another form of positive feedback that has been proposed as a potential memory store is a much shorter loop involving a single multisubunit molecule, CaM-kinase II (CAMKII). This molecule is normally inactive, but can be activated by increased Ca^{2+}. Among the substrates of the active enzyme is CAMKII itself. After the molecule becomes "autophosphorylated," it changes its properties and no longer requires Ca^{2+} to be active (*3*). Now comes the role for positive feedback (see part B). Suppose that Ca^{2+} has returned to resting levels and that the job of the kinase is to store the memory of the event that raised Ca^{2+}. Suppose further that a phosphatase dephosphorylates a kinase subunit. Because of positive feedback, other subunits that remain "on" may rephosphorylate this site, thereby retaining the "on-state" of the chemical system. This hypothesis (*4*) has gained substantial support, including the finding that CaMKII is required for

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