Tides and the Biosphere of Europa

A liquid-water ocean beneath a thin crust of ice may offer several habitats for the evolution of life on one of Jupiter’s moons

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The Copernican revolution began over 500 years ago with the realization that the Earth was not the center of the universe, but we still await its grand finale: The anticipated discovery of life elsewhere. Where else might we find life? The vast scale of the universe makes it virtually certain that there are other Earth-like settings. In our own solar system, Mars’s distance from the Sun makes it sufficiently Earth-like that, especially with increasing evidence for occasional liquid water, many are looking there for the first signs of extraterrestrial life. Recently, however, a new contender has emerged, and surprisingly it is from the cold outer solar system: It is Jupiter’s moon Europa.

Europa played an early role in the Copernican revolution as well. As one of the four satellites of Jupiter discovered by Galileo in 1610, Europa provided evidence that objects could orbit a celestial body other than Earth. Its steady motion around the planet, observable in the smallest backyard telescope, has been followed ever since. However, it wasn’t until 20 years ago that scientists realized that the tidal stresses imposed on Europa by the giant Jupiter could generate enough heat to maintain water in a liquid state, even so far from the Sun.

The possibility of liquid water opened the door to speculation about life, but water alone is not sufficient to sustain organisms. Life requires a nurturing environment, appropriate chemistry, a source of energy—a habitat. Now, late-20th-century observations by another Galileo—this time the Galileo spacecraft in orbit around Jupiter—show that tidal processes may create physical conditions that support a variety of interconnected habitable settings.

The extent to which tides govern the physical nature and potential habitability of Europa was quite unexpected. I have been part of the Galileo imaging team since the project began in 1977, and although I suspected that the Jovian tides would play a role in the rotation of the satellites, and perhaps govern some of their geophysical processes, no one fully anticipated the role that tidal processes would play in everything we see on these moons. Nor did I expect to find myself in the astrobiology business—which, for the moment, doesn’t study extraterrestrial life per se, but rather concerns itself with where alien life might be found. Here I recount some of what we’ve learned about Europa, and how these observations hint at the existence of habitable environments.

Waterworld

Planetary scientists have known for decades that Europa’s surface is predominantly water ice, beginning with ground-based spectroscopic studies by Gerard Kuiper, among others. The density inferred from gravity measurements suggests that the water layer may extend down as far as 150 kilometers below the surface, or somewhat less if part of the low-density layer is clay under the ocean. Although the surface is frozen, below it most of the water layer is probably liquid.

To the human eye, Europa would appear white and bland. Most images are processed with the color and contrast exaggerated to reveal surface features. In that way, even a distant view (Figure 1) manifests the two main types of geological terrain: the lines represent tectonic features, such as cracks and rifts and ridges, and the splotches represent disrupted, chaotic terrain. In fact, nearly all of Europa is covered by either tectonic or chaotic terrain, in roughly equal measure. Both appear to have been formed by processes driven by tides: Over the 85-hour day on Europa, tidal distortion creates stress that correlates well with tectonic features. And the chaos likely results from modest local and regional concentration of the tremendous internal heat of tidal friction.

The cracks and ridges and chaos make for a surface far too rough for a hockey game, and too challenging for any ice rink’s Zamboni. But neither can the weak ice support high mountains. Topography is at most a few hundred meters high.

Perhaps the most significant feature in any full-disk view of Europa is what we do not see: craters. In fact there are a few, such as Pwyll, the crater whose bright rays of splashed ice extend for 1,000 kilometers in every direction (Figure 1). But contrast the scarcity of craters with the heavily bombarded surface of our Moon, or with Europa’s neighbor Callisto. Given the large number of tiny bodies in the outer solar system, especially comets, Europa’s surface must be young to have avoided heavy bombardment. The tidal processes that drive tectonics and chaos have been so active recently that they have
completely resurfaced Europa in the cosmically short time since dinosaurs vanished from Earth. It would be surprising if they are not still in action.

How could tidal processes form the terrains on Europa’s surface? I discuss next how these processes seem to involve interaction of the surface with the ocean below, producing a variety of habitable niches. Comfortable niches would be stable for thousands of years, but individual niches would come and go over longer times. Not being too secure, organisms would need to adapt to a continuously habitable but ever-changing world, an essential driver for evolutionary advancement of life.

Tides
Just as the Sun and the Moon tend to elongate the Earth along an axis directed toward them, Jupiter elongates the shape of Europa along an imaginary line connecting the satellite to the giant planet. On the Earth, most of the continual reconfiguring is done by sloshing of the oceans, although the solid body of the Earth is also worked to some extent. Similarly on Europa, the solid body undergoes distortion, but most of the amplitude of tidal change is due to change in the shape of the liquid ocean under the ice.

Tides on Europa are different from those on the Earth in important ways. For one thing, Jupiter is huge, and it produces enormous tides on Europa (Figure 2). The height of the tide is about 500 meters at its peak on both sides of the moon. However, since Europa rotates nearly synchronously, keeping the same face toward Jupiter for hundreds of years, the daily tidal change is much smaller. The length of Europa’s day matches its orbital period of 85 hours, and the only reason the tide changes over the course of a Europan day is that...
its orbit is eccentric. At the time each
day when Europa is closest to Jupiter
the tidal distortion is greatest, raising
the tides by an extra 30 meters, and
when Europa is farthest from Jupiter the
tide decreases by 30 meters. This daily
working of the surface is what creates
frictional heat and stresses the icy crust
on top of the liquid ocean.

The daily tide has another important
effect. Because of its distorted shape, the
elongated ends of Europa are pulled by
Jupiter in such a way that it drives the
moon’s rotation to a rate slightly faster
than synchronous. As a result, the large
500-meter high tide moves around Eu-
ropa over the course of tens of thou-
sands of years. Over days or a few
years, however, only the 30-meter diur-
nal tide works the satellite.

Tides also tend to damp down or-
bital eccentricities very quickly. How
then does Europa’s orbit remain so ec-
centric? The answer goes back to a re-
markable feature of the orbits of the
Galilean satellites, evident even in
Galileo’s 17th-century observations.
During the 85-hour orbital period of
Europa, satellite Io completes exactly
two orbits and Ganymede makes exactly
half an orbit. Two centuries ago,
Laplace demonstrated how this 1:2:4
ratio of periods could resonantly en-
hance the mutual gravitational effects
of the satellites, so that they keep one
another’s orbits eccentric and maintain
the whole-number ratio of periods. The
orbital resonance is critical in maintain-
ing the tides that heat and stress Eu-
ropa, as well as Io (even more) and
Ganymede (considerably less so).

Cracks and Ridges
As the satellite changes shape under
the influence of tides, the thin ice shell
riding over the surface is stressed. The
large-scale linear patterns on Europa
correlate roughly with theoretical tidal
tension, suggesting that the lines, or lin-
eaments, represent cracks in the shell.

The Galileo spacecraft’s camera
zoomed in on selected locations, so we
can see how these cracks manifest
themselves at higher resolution. Figure
3a shows the intersection of two major
global lineaments, just north of the
splotch known as Conamara Chaos,
with a resolution (pixel size) of about 1
kilometer. We find that most global lin-
eaments at this scale prove to be double
dark lines, with a bright gap between
them. These features were named triple
bands when they were discovered on
Voyager images. Using similar termi-
nology, the double line down the center
of a highway would also be a triple
band, if one counts the space between
the lines.

Viewing the same region at higher
resolution, with a lower illumination
angle that shows topography and land-
forms, we find a very different picture

Figure 3. Triple-band features, such as the global lineaments (X-pattern) that cross just north of the chaotic terrain known as Conamara Chaos
(splotch, a), are revealed to be sets of ridges bordered by dark smudges when viewed in favorable lighting at higher resolution (b). A very
high resolution example (c), from the top of the center image, shows that ridges typically come in pairs, along either side of a crack. The
largest ridge pair (c) is about 2 kilometers across and 100 meters high. Ridges may be produced by tidal processes (see Figure 4).
(Figure 3b). Now we see that the global-scale lines prove to be complexes of ridges, roughly parallel and somewhat intertwined. The dark lines are revealed to be simply a very diffuse darkening along the surface adjacent to the ridge complexes. Yet this diffuse darkening was the only indication of the lineaments when viewed at low resolution, where the ridges were too small to be resolved. The ridges, even the complexes of multiple ridges, lie entirely within the gap between the dark margins. In terms of morphology, the major crack systems are manifested by ridges.

The relation between cracks and ridges becomes clearer when we note that ridges come in pairs wherever we see them. A close-up of a densely ridged area just north of Conamara is a good example (Figure 3c). Because cracks are manifested as ridges, and ridges come in pairs, ridges probably are built along both sides of a crack.

Ridges may result from tides (Figure 4). Once a crack is created, it is worked on a daily basis as tides distort the icy crust. Suppose a crack reaches liquid water. Opening the crack slightly will allow liquid water to rush up to the float line, just as cracks on a frozen lake fill nearly to the surface with liquid. Where water is exposed to the surface, it must boil in the vacuum as it freezes in the cold. Within a few hours the top of the crack is filled with a few meters of new ice. But then the tides reverse, and the crack begins to close. The fresh ice is crushed. As the walls of the crack slam together, ice is squeezed to the surface. At the beginning of the next daily cycle, the crack opens again, leaving ridges along both sides. Quantitative estimates suggest that enough material to build ridges a kilometer wide and 100 meters high, typical of larger examples, could be extruded in this way in about 20,000 years.

Cycloidal Crack Patterns

Global-scale lineaments are not the only indicators that tidal tension is the cause of cracks. Perhaps the best evidence comes from a distinctive and ubiquitous crack pattern in the shape of scalloped chains of arcs, in the geometric shape called cycloids. Figure 5 (left) shows an image of the southern hemisphere made by Voyager, in which these features were first seen, and some beautiful examples in the north are shown in Figure 5 (right). Numerous examples extend over 1,000 kilometers, including a dozen cycles or more, with each arc typically about 100 kilometers long.

These features were a mystery for nearly 20 years, until Randy Tufts and Greg Hopppa of the University of Arizona gave careful thought to the changes in tidal stress during the course of a Europan day. A crack begins when and where the tension exceeds the strength of the ice. Then, as the crack propagates across the surface, perhaps at a brisk walking speed of several kilometers per hour, the time of day advances and with it the strength and direction of the stress. The crack curves in response to the change in direction, and comes to a stop when the stress decreases below a critical threshold of strength. During the next few hours, while the stress is too weak to continue the cracking, its direction changes. Then, about a day after the cracking first began, the stress increases enough that the crack begins propagating again, in a new direction, leaving a cusp at the site where propagation was delayed. Thus each arc corresponds to one day’s worth of crack propagation.

In quantitative terms, this model fits observed patterns well, but it requires a substantial tidal amplitude for the stress to overcome the strength of the ice. That amplitude can only be reached if there is a substantial liquid ocean. For that reason, the existence of the cycloids became the first convincing evidence that there is indeed a global ocean on Europa. Corroboration came from later Galileo fly-bys when the magnetometer instrument detected modulation of Jupiter’s magnetic field, consistent with a conductive layer, such as a salty ocean, around Europa.

Strike-Slip Displacement

The surface of Europa is also modified by tectonic displacement of huge plates of surface ice. Consider the 1,000 kilometer-long dark band called Astypalaea Linea crossed by the more recent cycloids in the left-hand panel of Figure 5. A reprojected version, simulating a view from directly overhead, is also shown in Figure 6 (left). Geologist Tufts noticed two interesting characteristics of Astypalaea. Wispy white lines come up to the dark band from both sides and stop, and there are several parallelograms running along the length of the dark band. Both features are clues that Astypalaea is a strike-slip fault—there has been shear displacement of the opposite sides. When Tufts cut the image along the band and shifted the terrain on both sides, in effect running the shear backward in time, he found that the wispy lines reconnected and the parallelograms closed back up.

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Dilation
Large parts of Europa’s crust have also shifted through the dilation of cracks. As with shear displacement, we can cut and paste the images, reclosing the cracks to restore the surface to an earlier configuration (Figure 7). The opened cracks are called bands, and they tend to display a characteristic morphology that must reflect the infilling of the opening by material from below. Most striking are the sets of fine-scale parallel ridges within most bands, often symmetrical about a central groove.

This structure, and its similarity to double ridges, suggests a way that dilation may be driven by tides. Suppose the process of ridge formation is not very efficient, in the sense that some of the newly frozen ice within a crack does not get completely extruded during the daily squeezing phase. The crack may not be able to close completely. One day at a time, the crack may be forced open by increasing amounts of jammed material. Even if some other forces, such as currents in the underlying ocean, act to pull plates apart, the daily tidal working would have prevented a smooth, uniform rate of opening and may have been responsible for the fine-scale parallel lines that formed during dilation.

One other way that tides have driven dilation is by strike-slip displacements. If one large sheet of crust is moving past another, there may be a place at the end of the shear zone where the crust is pulled apart. Similarly, if strike-slip displacement occurs along a crack that is not straight, pull-apart zones may be created as part of the necessary geometry for accommodation. The large parallelogram that opened in the strike-slip fault Astypalaea appears to have formed in this way. What’s more, high-resolution images of Astypalaea show that it probably started as a cycloidal crack, and as it sheared a chain of pull-apart zones were created, each with the multiple striations around a central groove that are characteristic of typical dilational bands.

Dilation has been considerable on Europa, and as one looks back through the time sequence represented by cross-cutting and dissected features, it becomes evident that such extension of the surface has been going on for a long time. Given this source of new land, where is the sink? One possible explanation may come from the ubiquitous chaotic terrain.

As shown in the right-hand panel of Figure 6.

Strike-slip displacement is common on the Earth, where moving plates of crust slide past one another. The San Andreas fault is a good example, and it is similar in size to Astypalaea. But what could drive such shearing movement on Europa?

Again the answer appears to be tides. When Tufts, Hoppa and I looked at the stress across Astypalaea during the course of a Europian day, we found that it cycled through a condition of tension that would gape the crack open, followed by shear, followed by compression that would slam the crack shut, followed by shear in the opposite direction. This cycle repeated itself daily. Although the shear stress reversed itself during the course of each day, the crack would have been open and easy to shear in one direction, and closed and hard to shear in the other direction.

This process is analogous to walking, where we lift our foot from the floor, shear it forward, then press it against the ground and try to shear it back. Friction prevents the backslding. In the same way, a fault on Europa can take daily steps, shearing the terrain on one side past the other side. This theory should be able to predict the direction of shear at any place on the satellite, and indeed there is a fairly good match between what is calculated and what is observed.

Strike-slip displacement by tidal walking requires that cracks penetrate all the way through the ice down to the ocean. Otherwise, the daily steps of the walking process could not occur. This result has profound implications because cracks cannot go very deep into Europa. More than a few hundred meters down, or maybe a few kilometers at most, the weight of the ice would squeeze so hard that tidal tension could not overcome it. If cracks cannot penetrate more than a few kilometers, but they go all the way down to the ocean, it means that the ice layer on Europa must be very thin.

Figure 5. Cycloidal crack patterns are ubiquitous on Europa, including these in the southern (left) and northern (right) hemispheres. A typical chain of arcs may include more than a dozen cycles, with each arc about 100 kilometers long. Each arc corresponds to the propagation of a crack during a single day. (The southern hemisphere image was made by the Voyager 2 spacecraft, and is courtesy of the Jet Propulsion Laboratory and NASA.)

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Chaos!

Nearly half of the surface of Europa is made of chaotic terrain, visible as dark splotches in full-disk views of the moon. Its detailed character becomes evident in a sequence of images (Figures 3a, 3b and 8), which progressively zoom in on the archetypal example, Conamara Chaos. Here the surface has been disrupted, with rafts of older terrain displaced within a lumpy matrix.

Given the evidence from tectonics that the ice crust is thin, one plausible explanation for the chaotic terrain is melt-through, perhaps all the way from the ocean below. After the larger rafts of surviving crust move about, the water between them refreezes (filled with smaller lumps), leaving the characteristic appearance of chaotic terrain. Tidal heat, generated by internal friction, could be enough to keep the ice thin, and only modest concentrations are needed to melt patches of ice every now and then. Undersea volcanoes could provide such sources of concentrated heat.

Early descriptions of Galileo images reported that patches of chaos-type terrain had a characteristic size of about 10 kilometers across. This observation was interpreted to mean that these features were manifestations of the tops of convection cells in viscous solid ice at least 20 kilometers thick. That model of chaos formation was very different from the melt-through model, and completely inconsistent with the thin ice inferred from tidal-tectonic theory.

However, study of more recent images shows that the 10-kilometer size is an artifact of observational bias introduced by the limited imaging data available. In fact, patches of chaotic terrain can be more than a thousand kilometers across, and recent statistics show that smaller patches occur in increasing numbers as their size decreases. For many of the Galileo images the limits of resolution prevent us from detecting patches of chaos smaller than 10 kilometers across. So the lower limit of the observed size depends directly on the resolution of the images. This observational bias created the false impression that most patches were 10 kilometers across.

While the creation of chaotic terrain destroys older surfaces, chaotic terrain is itself destroyed by tectonic processes. In Figure 8, for example, we see a couple of cracks and incipient ridges wending through the rafts across Conamara Chaos. The history of Europa has been an ongoing interplay of resurfacing, by tectonics and by chaos formation, with each destroying what was there before and with each evidently involving a breakthrough of the ocean to the surface.

The continuous creation of so many openings may hold the key to the puzzle of the disappearing surface. Large sheets of surface can be readily compressed without leaving any signs of compressional stress if they are full of holes. In this way chaos may provide the sink that accommodates tectonic dilation.

Tides Drive Rotation

Tidal theory suggests that a satellite on a circular orbit will quickly come to rotate synchronously, with the same period as its orbit, much as Earth’s moon does (so that one hemisphere always faces us). But, because of Europa’s eccentric orbit, the Jovian-induced tides will maintain a spin rate slightly faster than synchronous so that Europa’s face toward Jupiter gradually changes.

This means that the tidal stress experienced by any given piece of real estate undergoes gradual changes as a consequence of the non-synchronous rotation. A crack that is actively worked, building ridges, may later freeze shut. A walking strike-slip fault may stop advancing and freeze in place. A cycloidal crack pattern may retain a record of the daily stress where it was formed, but now be much further east than where that happened.

In fact, cycloids can be used to determine the rotation rate. From tidal theory we can determine the longitude of a cycloid’s formation and the order in which the cycloids were formed over the geological history of the surface. We can place a limit on the duration of that history from the paucity of impact craters. By combining such information, Greg Hoppa has inferred a rotation rate for Europa that suggests that the hemisphere currently facing Jupiter was last in this position about 50,000
years ago.
At any given location on Europa, tidal tectonic processes are regular over thousands of years, but over tens of thousands of years, local conditions change in important ways.

Life?
The emerging picture of Europa as a world with an ocean that is intimately linked to its surface describes a physical setting that may provide everything needed for life. In contrast, the notion of a very thick ice layer that isolates the ocean from the surface provides a less hospitable setting. In that picture, the ecosystem is isolated from both oxygen and from sunlight. Scientists attracted to the possibility of life on Europa have been forced to imagine alternative biochemistries, assuming volcanism and hypothetical metabolisms. Even with the freedom to model deep-sea conditions unconstrained by any observations, there has been concern that life would be very limited, should it exist at all.

The thin-ice picture that follows from the ideas of tidal tectonics overcomes these problems. Consider a crack in the ice that is actively worked, opening and closing on a daily basis (Figure 9). At the base is liquid water, just above the freezing point, containing a mixture of substances from the moon’s interior and from external sources, such as comets. These substances leave the orange-brown traces visible wherever the ocean reaches the surface, whether through linear cracks or chaotic melt-through.

The surface of the ice is bombarded by energetic, charged particles from Jupiter’s magnetosphere, creating oxidants (such as oxygen and hydrogen peroxide), which get mixed back into the ice. Cometary material lands on the surface, depositing its suite of organic and other substances. Organisms within a few centimeters of the surface would be killed by the radiation, but enough sunlight could penetrate a few meters below to drive photosynthesis.

As a crack opens and closes, relatively warm seawater flows up and down each day. Much like tidal zones on Earth, this niche could conceivably support a rich ecology. Plants might anchor in the sunlight near the surface. Other organisms might grab, tick-like, onto the walls of the cracks and tap the passing daily flow as it mixes the disequilibrium chemistry. Some of them might break loose as ice melts beneath their feet, or be covered occasionally by new ice on the walls. Still others, floating like jellyfish, might simply go with the daily flow from ocean to surface.

Such a niche might be stable for thousands of years. But as Europa rotates relative to Jupiter, the crack moves...
to a different stress regime. The daily working might cease, sealing the crack closed and freezing organisms within it. For life to go on, some organisms must escape and travel through the sea to an active crack. Or the creatures frozen in the crack might be able to hibernate until a later thaw. They would only have to wait a million years or so, a feat demonstrated by Antarctic bacteria on Earth. By that time, a chaotic-forming crustal melt event is likely. Even sooner, new cracks might cross the area, releasing organisms into a new home.

As long as individual niches remain stable, they would allow organisms to be comfortable, secure and prosperous, but the longer-term change due to rotation would drive adaptation and mobility. These challenges are an important requirement for driving evolution to more complex and diverse forms of life.

Not only would the tidal tectonic processes provide habitable settings in the crust, they may also allow life to exist and prosper in the ocean by providing access to oxidants. Oceanic life would likely be part of the same ecosystem as organisms in the crust.

If there has been life on Europa, it is likely to be there now and to be readily accessible. The youth of Europa’s surface tells us that the physical processes and conditions that potentially allow for life on Europa have been in effect during the last one percent of the age of the solar system. Because they were so recent, they likely continue today. Moreover, should there be a biosphere on Europa, it may extend from deep in the ocean up to within a few centimeters of the surface.

This possibility makes Europa exciting target for future exploration. Extraterrestrial life may be more accessible than previously thought. Rather than needing to drill down through many kilometers of ice, we may be able to scoop up organisms at or near the surface. What would make exploration easier for us is not necessarily good for the Europans, however. If the near-surface is as fecund as now seems plausible, Jupiter’s moon may be vulnerable to contamination by terrestrial hitchhikers on our spacecraft. Explorations need to be planned with care.

Even if Europa proves to be sterile, the complex suite of geophysical processes and their unique relationships with geological and dynamical phenomena make Europa one of the most active and exciting bodies in the solar system.

Bibliography


Links to Internet resources for “Tides and the Biosphere of Europa” are available on the American Scientist Web site:
http://www.americanscientist.org/ articles/02Articles/greenberg.html