edge and delayed the spawning of new moonlets.

After the lag, the Moon began efficiently accreting melt from the inner disk. But as decades passed and material dissipated, the disk torques weakened, and eventually any newly forming clumps were scattered into high-eccentricity orbits by the Moon and fell back to Earth.

## Adding chemistry

The new work tackles the question of how late in the accretion process the volatiles in the inner disk could have cooled enough to become part of the migrating melt that ended up on the Moon.[1] To evaluate the melt's composition, the team incorporated two additional models into the dynamical simulations. A thermal model estimates the temperature and partial pressure of the clumps as a function of when they form at the Roche limit. A second, chemical model estimates the extent to which various volatile and more refractory elements partition into the melt at the temperature and vapor pressure they experience just prior to reaching the Roche limit.

The researchers found that the clump-formation temperatures remained above the condensation temperature of potassium (about 3000 K at the relevant disk pressures) until at least 98% of the Moon had accreted. The outer roughly 60% of the Moon must therefore have formed from moonlets depleted of potassium, sodium, and their more volatile cousins, such as zinc; that prediction has been borne out by the Apollo samples. By the time those elements were cool enough to appreciably condense, the Moon had spiraled away out of reach.

## Water inside the Moon?

The volatile content of the Moon's deep interior—the part created by the first batch of moonlets—is uncertain. The team says that portion of the Moon should contain the same abundance of volatiles as Earth does, covered by the later accumulation of an overlying 100- to 500-km volatile-poor layer. Assuming that the Moon was never molten enough to stir up its contents and that little gas evaporatively escaped, "there's really no other place for the volatile elements in the vapor to end up," says Canup, "since they were already emplaced outside the Roche limit immediately following the giant impact."

The disk in the team's new simulations was anhydrous; its two-phase silicate-rock composition supplies all the oxygen required to build a realistic Moon. Nonetheless, the disparate measurements of water content among lunar samples are tantalizing. Whereas most rocks found on the surface are bone dry, glass beads spewed onto the surface by volcanic fountains from the deep interior 3 billion–4 billion years ago contain water concentrations as high as 46 parts per million by mass (see the Quick Study by Lindy Elkins-Tanton, PHYSICS TODAY, March 2011, page 74; for a review, see reference 3). That's comparable to the driest parts of Earth's mantle.

**Mark Wilson**

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2. See, for example, J. Salmon, R. M. Canup, *Astrophys. J.* **760**, 83 (2012).
3. E. H. Hauri et al., *Earth Planet. Sci. Lett.* **409**, 252 (2015).

# Ion channels facilitate long-distance communication among bacteria

The specialized membrane proteins' function, puzzling in a single bacterial cell, becomes apparent when the cell joins a large colony.

The membranes of all living cells contain proteins called ion channels that allow ions to move in and out of the cells. The flow of ions through those channels helps to regulate the electrostatic potential difference across a cell's membrane.

In the case of multicellular organisms, cells communicate with each other by

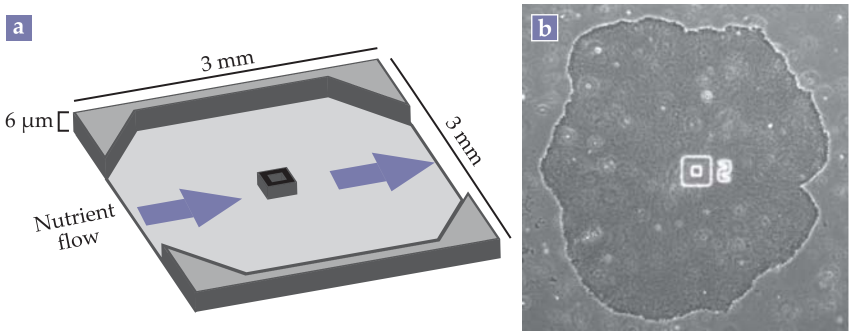



**FIGURE 1. BACTERIA COMMONLY FORM BIOFILMS,** densely packed cellular communities that can contain billions of cells. **(a)** A microfluidic device with a constant flow of nutrients allows precise control over the biofilm's environment. **(b)** The microscope image shows a *Bacillus subtilis* biofilm grown in such a microfluidic device. The number 2 is a label. The square in the middle of the device is a cell trap that initially helps to attach the biofilm to the surface. (Panel a adapted from ref. 2; panel b courtesy of Gürol Süel.)

opening and closing specialized channels that let only specific ions through. For example, the coordinated opening and closing of sodium and potassium channels and the associated inflow of $Na^+$ and outflow of $K^+$ propagate a positive voltage pulse—a nerve impulse—down a neuron.

Single-cell organisms such as bacteria also contain various ion-specific channels. In fact, biologists have gained much of what they know about the structure and function of ion channels by looking at proteins harvested from bacteria. What the bacteria use them for has long been a puzzle.

Gürol Süel (University of California, San Diego) and his colleagues have shown for the first time that bacteria also communicate via ion channels. The researchers observed that in densely packed colonies of *Bacillus subtilis*, the bacteria's growth cyclically slowed down and sped up. Those oscillations, they discovered, were coordinated by the release of $K^+$ by cells in the colony's interior.[1]

## Mimicking nature

Süel and his colleagues suspected that the difficulty in pinpointing the function of bacterial ion channels had to do with the way bacteria are studied. Lab studies typically use bacterial cells suspended in a liquid. "Well-mixed liquid cultures are not how bacteria exist in nature," he says. Bacteria more commonly form dense colonies of cells called biofilms that attach to a surface.

As shown in figure 1, the researchers grew their *B. subtilis* biofilms in microfluidic devices with continuous flows of a nutrient broth. Süel explains that the microfluidic devices allowed his team to precisely manipulate the environmental conditions around the bacteria.

The biofilms exhibited collective behavior that surprised Süel and his colleagues. Despite the continuous flow of nutrients, once a biofilm grew to be

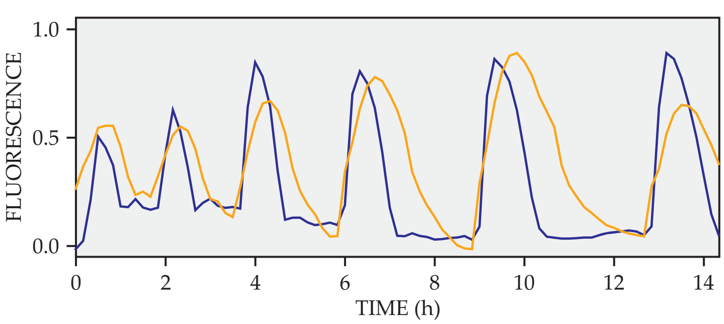



**FIGURE 2. FLUORESCENCE SIGNALS** from a voltage-sensitive dye (blue) and a potassium-sensitive dye (yellow). Fluorescence is given in arbitrary units. The correlation between the two signals indicates the strong connection between the bacteria's cell-membrane potential and the $K^+$ release. (Adapted from ref. 1.)

bigger than about 600 μm in diameter, biofilm growth began to periodically slow down and speed up.[2] The researchers surmised that those oscillations reflected an internal conflict within the colony between long-term survival and short-term growth.

Cells at the film's edges protect the interior cells from external crises, such as a sudden change in pH or the presence of antibiotics. The long-term maintenance of interior cells is a critical hedge against such threats. But for the colony to expand, cells at the periphery, where film growth largely occurs, often use up a lion's share of available nutrients. That overconsumption of nutrients—glutamate in the case of *B. subtilis*—at the edges can starve the interior.

Süel and his colleagues realized that the biofilm colony balanced those two requirements by developing a metabolic codependence between the interior and peripheral cells. The cells break down some of the glutamate in the nutrient broth into ammonium. They then combine the ammonium with glutamate to make the amino acid glutamine, a necessary ingredient for bacterial growth.

When the interior cells are starved of glutamate, they stop producing ammonium. The reduction in available ammonium is enough to halt the growth of the peripheral cells; glutamate then becomes available in the interior.

## Sending out an SOS

Although the ammonium–glutamate balancing act is sufficient to explain the growth oscillations, the high degree of synchronization in those oscillations suggested that additional coordinating mechanisms must be at play. Because a cell's ability to absorb glutamate or retain ammonium depends on its membrane potential, Süel and his colleagues suspected that the mechanism was electrochemical.

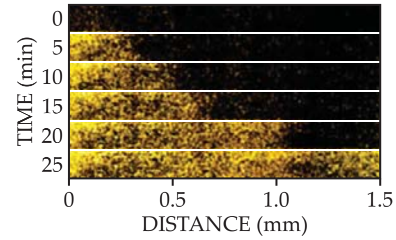



**FIGURE 3. ACTIVE PROPAGATION** of potassium ions. This time series of fluorescence microscope images shows that cells in the interior of a biofilm release $K^+$ (yellow) as a metabolic distress call to cells at the periphery. Neighboring cells actively amplify and relay the signal by releasing their own $K^+$. (Adapted from ref. 1.)

Using a voltage-sensitive fluorescent dye, the researchers found periodic fluc-

# PHYSICS UPDATE

These items, with supplementary material, first appeared at www.physicstoday.org.

### A QUANTUM DERIVATION OF A CLASSIC MATH FORMULA

When a quantum mechanical Hamiltonian cannot be solved exactly, one can estimate system energies with a technique called the variational method. The idea is to calculate the energy expectation value for a trial wavefunction with one or more tunable parameters and determine the minimum energy that results from varying the parameters. As an exercise to help his students get a feel for the approach, the University of Rochester's Carl Hagen applied it to a solvable system—the hydrogen atom. With the help of Rochester colleague Tamar Friedmann, he found to his surprise that the exercise yielded a representation for $\pi$ published in 1655 by mathematician John Wallis:

$$\frac{\pi}{2} = \frac{2\cdot 2}{1\cdot 3}\,\frac{4\cdot 4}{3\cdot 5}\,\frac{6\cdot 6}{5\cdot 7}\cdots.$$

Hagen and Friedmann considered a trial wavefunction that had the same angular behavior as the hydrogen atom but different radial behavior. They calculated how the minimum variational energy of their trial form depended on the angular momentum quantum number $\ell$ and divided that energy by the exact energy of a hydrogen atom with angular momentum $\ell$ and principal quantum number $n = \ell + 1$. According to the variational principle, the ratio of energies

$$\frac{(\ell+1)^2}{(\ell+\frac{3}{2})}\left[\frac{\Gamma(\ell+1)}{\Gamma(\ell+\frac{3}{2})}\right]^2$$

must be $\leq 1$. (The $\Gamma$ function is the famous generalization of the factorial.) In fact, as $\ell$ approaches infinity, the ratio approaches 1. The Wallis representation then follows from the recursion property of the $\Gamma$ function, $\Gamma(z+1) = z\Gamma(z)$, and the specific values $\Gamma(1) = 1$ and $\Gamma(1/2) = \pi^{1/2}$. Given the different radial behavior of the trial and exact wavefunctions, it may seem surprising that the ratio of variational to exact energies tends to 1 for large $\ell$. The authors note, however, that in the infinite-$\ell$ limit, both wavefunctions describe electrons on sharply defined trajectories; the quantum fuzziness that distinguishes the electron orbits for finite $\ell$ goes away. (T. Friedmann, C. R. Hagen, *J. Math. Phys.* **56**, 112101, 2015.)

—SKB

### ATMOSPHERIC WAVES ABOVE NEW ZEALAND

When air blown across a sea or a plain encounters a mountain range, it's pushed upward into the cooler air above. The difference in buoyancy between the two air masses sets up a standing gravity wave—a mountain wave—leeward of the range. Mountain waves, in turn, engender other gravity waves that lift energy and momentum into the stratosphere and mesosphere. (See Backscatter in PHYSICS TODAY, June 2006, page 96.) To characterize those waves, Bernd Kaifler of the German Aerospace Center and his collaborators developed a compact, mobile light and detection ranging (lidar) experiment. Between June and November 2014, they installed it in one of the world's strongest sources of mountain waves: New Zealand's Southern Alps. (The accompanying photo shows waves above the site.) The experiment sent light pulses upward into the atmosphere and measured the echoes' travel time, which yields the altitude, and their intensity, which is proportional to the local atmospheric density. Thanks to the lidar's power, the experiment could quantify gravity waves up to 80 km, which corresponds to the top of the mesosphere. As expected, the gravity waves were most active during southern winter, when the prevailing westerly winds are strongest. Yet even during the summer, the gravity waves pervaded the stratosphere and mesosphere. The biggest surprise came when the researchers correlated the speed of the surface winds with the altitude of the gravity waves: Moderate, not strong, winds are the most effective

tuations in membrane potentials that went hand in hand with the growth oscillations. When they added glutamine directly to the nutrient broth so the bacteria didn't have to make it out of glutamate, the fluctuations stopped. Those results demonstrated a connection between the growth oscillations and membrane potentials.

The next step was to figure out what ions were involved in the membrane-potential changes. Süel and his colleagues used fluorescent dyes that bind to either $Na^+$ or $K^+$. They found that changes in the extracellular concentration of $K^+$ were directly correlated with the changes in the membrane potential, as shown in figure 2.

They deduced that when peripheral cells overconsume glutamate, the starved interior cells open a potassium-specific ion channel called YugO. As shown in figure 3, the $K^+$ signal propagates across the length of the film. Crucially, the signal doesn't decay—a sign that neighboring cells actively amplify the $K^+$ signal by releasing their own $K^+$. In effect, the starving interior cells send out a metabolic SOS, and neighboring cells relay that distress call to the biofilm's periphery like a bacterial bucket brigade.

The added extracellular $K^+$ changes the peripheral cells' membrane potentials and hinders them from absorbing glutamate. Glutamate then becomes available to the interior cells, the ion channel closes, and the cycle starts over.

Süel notes that the signaling mechanism in *B. subtilis* is similar to a slowly moving wave of depressed membrane potentials in the brain, which has been associated with migraines. Both involve extracellular $K^+$, and both are triggered by metabolic stress. "In a sense, the bacteria in biofilms communicate like neurons in the brain."

The inner workings of the YugO channel—how it opens and closes in response to glutamate shortage or extracellular $K^+$—are still largely a mystery. In addition, the researchers want to see if other bacterial species use similar electrochemical communication.

Another avenue that Süel wants to follow is to see if $K^+$ signals travel beyond a single colony. In their work, they observed that extracellular $K^+$ concentrations extend past the biofilm edge. Potentially, the $K^+$ signal could reach cells or other colonies not in direct contact with the biofilm.

**Sung Chang**

## References


1. A. Prindle et al., *Nature* **527**, 59 (2015).
2. J. Liu et al., *Nature* **523**, 550 (2015).

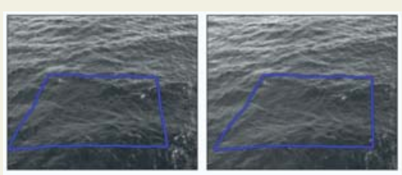

at sending gravity waves into the upper mesosphere. That finding overturns the previous assumption of a linear relationship that was built into climate models. (B. Kaifler et al., *Geophys. Res. Lett.* **42**, 9488, 2015.) —CD

### DISCHARGE-BUBBLE LUMINESCENCE

When a bubble in a liquid collapses, the gas inside it can get compressed and heated to the point that it spontaneously ionizes. The resulting plasma is short-lived, and when its atoms recombine it gives off a flash of light. (See PHYSICS TODAY, April 2012, page 18, and the article by Detlef Lohse, PHYSICS TODAY, February 2003, page 36.) The process was first studied using ultrasound-generated bubbles some 10–100 μm in size that lasted tens of microseconds; the picosecond light bursts from the collapsing bubbles earned the moniker sonoluminescence. Dielectric breakdown at the focus of a pulsed laser can also induce bubbles—an order of magnitude larger and lasting an order of magnitude longer than the acoustic bubbles, with flashes lasting nanoseconds. A new paper by Keping Yan and colleagues at China's Zhejiang University examines a more recent source of luminescing bubbles: electric discharge. Connecting an underwater electrode to a pulsed power source, the team produced an oscillating bubble for a sufficiently strong voltage pulse. A high-speed camera, capturing a frame every 25 μs, recorded the bubble expansion and collapse. The discharge-induced bubbles grew up to a centimeter across and lasted for milliseconds, and the luminescence lasted some tens of microseconds. A key question of bubble collapse is the internal temperature, and the longer duration of discharge-induced luminescence should provide opportunities to accurately measure the emission spectrum. The researchers' modeling suggests their bubbles reach peak temperatures of about 7000 K. That's close to what's been reported for ultrasound and laser bubbles; the temperature determination in all the systems, however, depends on mass transfer, chemical reactions, and other modeling details of the collapse dynamics. (Y. Huang et al., *Appl. Phys. Lett.* **107**, 184104, 2015.) —RJF

### WATCHING WAVES

Wind blowing across the sea induces waves of various heights, wavelengths, and speeds. Although the waves' rich spectrum can be derived from linear theory, nonlinearities are significant, even when the wind is just a breeze. Measuring the wave spectrum is challenging because it entails tracking the height of the sea surface over a range of length and time scales. Fabrice Ardhuin of the French Research Institute for Exploration of the Sea in Plouzané, Brest, France, and his collaborators have met that challenge using high-speed stereoscopic video. Their experiment is set up on a fixed platform situated 500 meters off the southern tip of the



Crimean Peninsula. From a vantage 11 meters above the surface, two 5-megapixel cameras monitor the same, roughly 100-square-meter patch of the Black Sea and gather data at 12 frames per second (see figure for two typical frames and the study patch outlined in blue). Correlating the two images—frame by frame, pixel by pixel—yields the surface elevation. Fourier transforming the elevation yields the spectrum. The team now reports the results of an experimental run that took place in October 2011 on a day when the wind was a strong steady breeze of 13 m/s. Thanks to the cameras' ability to resolve propagation directions, the researchers could measure the amount of wave energy that travels in opposite directions. Because the waves' interactions contribute to the background noise detected by underwater seismometers, the state of the sea might one day be characterized from seismic data alone. Among their other findings: Waves 1/15 the length of the dominant spectral component tend to travel 70° away from the wind direction. (F. Leckler et al., *J. Phys. Oceanogr.* **45**, 2484, 2015.) —CD PT