Splendor in the Dark

Scientists have discovered that fish in the ocean glow, gleam, spark, and light up like neon signs. Now they want to know how

By Jack McClintock

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In 1984, encased in a huge yellow metal diving suit equipped with foot-controlled thrusters, deep-sea biologist Edith Widder sank into the Pacific Ocean on her first deep dive. With her suit's lights turned on, she watched shrimp, fish, and jellyfish rising past a clear, bubblelike dome that covered her head. Beyond the reach of the artificial lights, the sea was pitch black. Then at 800 feet, she switched them off.

As her eyes adjusted, she says, "little dots like fairy dust, splats like puffs of liquid, sparks like embers thrown up from a campfire" emerged from the dark. "Except all these lights were blue. It was absolutely mesmerizing, and I couldn't believe how much there was. It was everywhere!"

What Widder observed was bioluminescence, the lighting that sea creatures use to lure prey, attract sexual partners, and deter predators. Some of the flashes had no particular shape. Others outlined a creature or disguised it in an almost psychedelic array of dots, flashes, pulses, gleams, expanding rings, steady glows, and bursts of light. Some of the lights were tiny: The flash of a dinoflagellate is just a tenth of a millionth of a watt and lasts but a tenth of a second. Certain jellyfish, by contrast, can generate expanding rings of glowing blue light for half a minute or more. It is an extraordinary phenomenon that can't be put easily into words. Widder simply says, "You have to see it." Once she did, "there was no turning back."

Fireflies, some earthworms, fungi, and bacteria can do it, and a field full of fireflies with light pulses in sync can be fascinating to watch. But nothing above the sea's surface compares with the display of light below. Bioluminescence is found in every ocean, in every sea, from surface to seafloor. In the upper 3,200 feet of the ocean, as many as 90 percent of the creatures are bioluminescent, says Laurence Madin, a pioneering marine ecologist at Woods Hole Oceanographic Institution. Earth's most abundant vertebrate, an inch-long fish called the bent-tooth bristlemouth, is bioluminescent. Another, the viperfish, has lighting that looks as if it came from fiber optics at the base of its protruding teeth and at its fins. There is an illuminated lure that arcs out from the top of its head, a light under each eye to help it see, lights on its belly for camouflage, and tinted photophores in a mucous layer along its belly and back. So when startled, the viperfish presents an outline of itself, like a neon sign hung outside a bait shop.

Although reported for centuries, bioluminescence is one of the great mysteries of the sea, and scientists are only now asking important questions about it. "What organisms are bioluminescent, and where are they found?" asks Peter Herring, a marine scientist at the Southampton Oceanography Centre in Britain and author of *The Biology of the Deep Ocean*. What are the characteristics of these emissions, how are they achieved—and, most important to the ecologist, when and why is bioluminescence produced? Herring says we know a good deal about which creatures glow and where they live. But the question of when and why bioluminescence is produced is complicated and can be answered only with more field observations. "That is ultimately the only way we are going to understand what bioluminescence is really for and how important it is to the success of those organisms that have it," Herring says. "Part of its intrinsic fascination is, of course, that we humans can't do it."

All light comes from the same physical process: An electron circling the nucleus of an atom in its customary orbit is energized—often by heat—and moves into a higher orbit. As it drops back to its normal, lower orbit, it releases some energy in the form of light—a photon. In incandescent light, the trigger to push electrons into a higher orbit is heat provided by electricity passing through a carbon filament in a vacuum; in bioluminescence, the electrons are pushed up by two chemicals working together. One, known as a luciferase, stimulates another, called a luciferin, causing it to oxidize, moving electrons up into higher orbits that decay and produce a glow. The resulting light is usually at the blue-green range of visible light. At the other end of the range, red light is quickly absorbed in seawater.

Although most organisms have evolved to produce only blue-green light, there are exceptions—some animals can see red. The dragonfish not only sees red but can also create, from an organ just below its eye, a red beam to illuminate prey or communicate with its own kind without being detected. "It's like a flashlight and a sniperscope," says Sonke Johnsen, an assistant professor of biology at Duke University who worked with Widder as a postdoctoral student. "We don't know how far the beam goes, but it doesn't reach very far. Everything down there is slow moving, it's cold, there's not much food—it's kind of a sad little life, really. You don't want to see things too far away, to be distracted and waste time and energy."

Some jellyfish also seem to exploit red pigment's ability to absorb blue light: Their stomachs are colored red, so when they swallow their glowing blue-green prey, the meal seems to vanish, hidden behind a red wall. That "keeps their lunch from giving them away," says Madin.

That Human Touch

Courtesy of GloFish

They look like ordinary pet fish, the kind found in thousands, if not millions, of home aquariums around the country. Or at least they do in daylight. Turn on a black or ultraviolet light, however, and they glow bright red like neon signs. Meet GloFish, the world's first genetically engineered pets—tropical zebra danios that fluoresce red thanks to a gene scientists transplanted into their embryonic DNA. Put on the market earlier this year, GloFish became an overnight sensation among hobbyists. "Everybody's really excited about them," says Noelle Boyd, a spokeswoman for Yorktown Technologies, the Texas company that creates them. "From the distributors we've been hearing that they've never seen so much demand."

Not everyone gives the $5 fish glowing reviews. In a recent survey by the Opinion Research Corporation, roughly 84 percent of American adults said that companies should not be permitted to genetically engineer animals for sale as pets. In December the California Fish and Game Commission banned their sale, fearing GloFish could open the way for a raft of genetically engineered animals. A month later the Center for Food Safety and the International Center for Technology Assessment jointly filed a federal lawsuit in Washington, D.C., against the Food and Drug Administration, trying to force a halt to the fish's sale. "We'd like GloFish off the market," says Craig Culp of the Center for Food Safety. "There are various concerns for human health that have not been evaluated."

The FDA opposes the suit, arguing that GloFish do not pose a risk to public health because they are purely ornamental and not meant for consumption. Further, it says, zebra fish are native to the tropics, so even those that wind up in public waterways could not survive in the colder North American climate. Indeed, millions of (nonglowing) zebra fish are sold each year, but the U.S. Geological Survey has yet to discover a single population of them in North American waters. The suit is still pending.

Ironically, GloFish are the product of research aimed at helping the environment. The creatures were developed by scientists at the National University of Singapore as part of an ongoing attempt to make transgenic fish that light up when exposed to such chemical toxins as PCBs, which are known to cause cancer in humans. Once the glow gene, which comes from sea coral, is transplanted into a fish, it remains fluorescent for the rest of its life, as do all its offspring. Zebra fish are ideal for this sort of research because of their small size and rapid reproduction rate. An early prototype, GloFish was meant to show that

such an idea was feasible. “You have to invent the lightbulb before you invent the switch to turn it on,” explains Boyd. “They had to first figure out how to make a fish glow all the time before they could figure out how to make it glow in the presence of toxins.”
—Alex Stone

The underwater creatures that stick with the blue-green glow have evolved useful techniques too. For example, some sea creatures, like the dragonfish, use bioluminescent appendages as lures to troll for food. Others may use the light to troll for mates. The male sea firefly, a crustacean the size of a sesame seed, squirts out light that hangs as a bright dot in the water, then zips upward and squirts out another and another, leaving a string of hanging dots spaced out like smoke signals. The spacing is species specific; mate-ready females can go to the head of the dot string and find an appropriate male. “That’s a real mindblower,” Widder says. “It’s a pretty complex behavior for these little guys.”

Some sea life uses light as a weapon. One fish, the shining tubeshoulder, literally squirts light out of a tube on its shoulder into the face of an enemy, much as a squid shoots ink. One specimen, brought up from the deep and into a fluorescent-filled shipboard laboratory, flashed so brightly that researchers gasped. “That would definitely blind a predator,” Widder says, laughing.

Photograph by Ben Baker/Redux Pictures

Edith Widder (left) and pilot Craig Caddigan sit in the Johnson-Sea-Link submersible, which is capable of going to depths of 3,000 feet. Over the years Widder has invented several devices that are attached to the sub to photograph and measure various deep-sea populations of bioluminescent fish.

Other ocean creatures use bioluminescence as a warning: *I’m toxic; leave me alone*. Widder has recorded unusual displays by bamboo coral off the coast of the Carolinas. When touched, the coral lights up like a Christmas tree and disgorges sheets of thick, gill-clogging slime. The sea pen, long and slender, also had a surprise for Widder. When pinched with tweezers in a lab test, it shot green light down its thin stalk. When the light reached the plume at the end of the stalk, it turned blue. Widder thought the intent might be to draw a predator’s attention to a less vulnerable area. But when she tested the idea by pinching the stalk’s other end, the light changed direction and shot back the other way. When she pinched the middle, the light moved outward in both directions at once. She thinks it’s like a burglar alarm—to lure whatever creature is in the sea pen’s vicinity into attacking its attacker. Tiny dinoflagellates seem to use their bioluminescence to the same effect, “like a scream,” Widder says. When predators try to eat them, the dinoflagellates flash, lighting up the water. Creatures grazing on the dinoflagellates “don’t want to be lit up and munched on” by other predators, she says.

Still others use light as camouflage or “counterillumination.” The cookie-cutter shark employs a complicated lighting strategy to attract a meal. Seen from below, its belly glows with blue light, making it difficult to distinguish against the backdrop of sunlight coming from the ocean’s surface—except for a small dark band near its mouth. To hungry tuna attacking from below, the band might resemble a small fish.

Such camouflage techniques are not flawless. Sonke Johnsen has found that in clear water some creatures can see with high sensitivity. “They can detect lower light levels, a hundred times as low as we can see. But the evolutionary trade-off is that they sacrifice clarity,” he says. “We were looking at how it balances out, and we suspected that the water blurs their vision. But it turns out that in the clear water they can really pick patterns out. Very few of them have even illumination. There's nothing to hide behind in the open ocean," Johnsen continues, "but they still have to hide, so they use every trick in the book to stay hidden. But their predators are using every trick in the book to find them."

Widder marvels at all the cleverness. "We live in a lighted world," she says. "We have burglar alarms on cars to make noise to attract attention and scare off the burglar or bring the police. But the bioluminescent world is a minefield. Any movement will reveal you to predators."

That's why the U.S. Navy has funded some of Widder's research. Motion in the water—a diver, a landing craft, a submarine—stimulates plankton to glow. In November 1918, the last German U-boat sunk during World War I was spotted by the bioluminescence it stirred up in the Mediterranean. Carrier-based aviators in World War II sometimes found their ship after a mission by following its bioluminescent wake. And during the Gulf War, Navy SEALs had to change a landing site to avoid bioluminescence that might have revealed their presence. Now the Navy is hoping scientists can chart the location, amount, and seasonal fluctuations of bioluminescence worldwide. In a world of submarines and nighttime operations, it would be exceptional intelligence to have.

As head of the bioluminescence department at Harbor Branch Oceanographic Institution in Fort Pierce, Florida, Widder, 52, is the leading investigator of this mysterious light and the animals that display it. She believes it is one of the most important processes in the ocean. "There's so much bioluminescent energy being created and used," she marvels, "and we don't know anything about it. In studying the ecology of the ocean, ignoring the most important form of communication is like studying the ecology of land while ignoring animal vision."

The oceans' midwater zone, a vast area between 650 and 3,200 feet deep, is Earth's greatest ecosystem. "There are more animals there than in all the other habitats," Widder says. Scientists have explored less than 5 percent of it, and thus far, Widder says, they've done so with "embarrassingly primitive" tools. "I defy you to name another science that depends on 2,000-year-old technology: dragnets. Nets catch only the slow, the stupid, the greedy, and the indestructible—which then deteriorate on shelves in jars. They destroy the gelatinous animals, and they miss huge players—the big stuff that can outrun you. So you get a one-dimensional view of ocean life and no idea of distribution. It's . . . primitive!"

Widder became determined to develop more sophisticated instruments. She started in graduate school. In 1984 the Navy asked her adviser, biologist James Case, to find a way of measuring oceanic illumination, and he recruited Widder as coinvestigator. It was a good match. "The Navy wanted to know how much light there was, and I wanted to know who's making it and figure out the ecology," Widder says. "I wanted to go to a chunk of ocean and say, 'Oh, it's all copepods here,' or whatever."

But it wasn't easy to do that. Scientists had already tried lowering sensors and cameras to measure bioluminescence, but as the measurements bobbed up and down with the mother ship's motion, they stimulated more bioluminescence. And creatures were known to change their natural behavior when they detected measuring devices nearby. So Widder covered a hoop with some netting from a research ship's supply store and mounted it on a Deep Rover submersible with a video camera focused on the plane of the net. She called it the splat-cam—for spatial plankton analysis technique. When animals hit the net as the sub moved through the water, they were stimulated to glow and the camera recorded the events. Widder became the first scientist to count the numbers of bioluminescent creatures per cubic meter in a particular part of the ocean.

Widder and Case then built what they called a high-intake defined-excitation bathy-photometer—or Hidex-BP, for short. They mounted it on a framework and towed it through the water. It pumps 20 liters (about 5.3 gallons) of seawater and plankton per second through a “light tight” collection chamber large enough to capture even fast swimmers and keep them inside long enough for the device’s fiber-optic instruments to record and measure, in photons per liter, the size, duration, and number of an organism’s flashes.

From her graduate study of dinoflagellates, Widder knew that an animal’s first flash is the brightest and that to obtain clear readings, the creature must be stimulated and contained long enough to measure all the light given off. No one had managed to do this systematically before, and the device was successful. The Navy’s entire bioluminescence database rests on the device and a second-generation version.

Widder is working on a third-generation unit that will offer better mapping of the distribution patterns of light. Over the years, better instruments have been the key to Widder’s research. “I’ve combined all my interests by engineering toys for ocean exploration,” she says.

Courtesy of Edith Widder/Harbor Branch Oceanographic Institution

Note how the oval behind the eye of the aptly named loosejaw, found off the Canary Islands southwest of Spain, changes in this series of photographs. The fish’s light organ closes when not in use or to escape detection.

Sometimes a scientist is lucky enough to recover a rare and remarkable animal. That happened to Widder in 1997 when she took a Johnson-Sea-Link submersible down to 2,477 feet in the Oceanographer’s Canyon off Georges Bank in the Gulf of Maine. There she saw an octopus, which started glowing back in the lab. At the time only two of 43 genera of the creatures were known to display bioluminescence. Here was another. “It was evolution caught in the act,” she says. “The octopus’s suckers were turning into light organs.” She thinks the creature once lived on the bottom in shallow water and then moved into deeper, darker environs, where it evolved the light-up suckers to attract food. “The suckers actually twinkle, and they look like the dinoflagellates on which copepods feed,” Widder says. “The copepods approach, and when the octopus slowly closes into what we call a turban posture, the copepods get stuck in mucus surrounding the octopus’s mouth. The octopus gut shows that copepods are what they eat.”

Revelation at the bottom of the sea is normal. “Every time I go down there I see something I’ve never seen before,” Widder says. “And every four or five times, I see species *nobody’s* seen before.”

Quantifying bioluminescence was a leap that allowed Widder to accurately describe the midocean environment as a minefield. She could then move on to bioluminescence as a tool for locating and mapping various populations of animals and observing how they overlap. Scientists once thought of the ocean as a vast, undifferentiated soup, but Widder’s work shows that it has a high level of organization and stratification. For instance, copepods, which are tiny crustaceans, tend to gather and feed at certain levels of salinity and temperature. That knowledge, of course, raises further questions. Are other fish more likely to be there, too, feeding on copepods? Do other creatures avoid high levels of bioluminescence, which might attract predators?

Widder soon realized that she could identify many animals by the type and duration of flash they made—jellyfish, for example, might appear as a bright circle in the darkness. That meant bioluminescence could tell her which animals were where, which others they associated with, how they interacted, and how such variables as light, salinity, temperature, and pollution affect their habits and distribution. She could study behaviors and relationships, adding significantly to science's understanding of undersea life.

The field is young and full of surprises. At the Monterey Bay Aquarium Research Institute, for example, marine biologist Steven Haddock recently discovered that certain jellyfish cannot manufacture their own luciferin and that they probably get it from eating small crustaceans. Yet jellyfish are among the oldest creatures on Earth, and one might have presumed their bioluminescence evolved early on.

But bioluminescence research is held back by the difficulty, danger, and expense of getting where the action is. "If we put the same funding into the ocean as NASA does into space, the results would be tenfold," Widder says. "Drugs from the sea is just one example—you'll never get that from space."

If Widder had NASA's budget, she would build undersea observatories to unobtrusively sit and watch creatures in search of an answer to a central question: What's the background level of bioluminescence when humans are not there to stimulate its production? Without that budget, she hopes her new invention, called Eye in the Sea, will help. The device is an infrared and visible-light camera that will sit on a tripod on the seafloor, emitting light on a wavelength believed to be invisible to most sea animals. It's a tricky design problem: The Eye has to be stable, leakproof, and capable of amplifying light on a suitable wavelength the way night-vision goggles do.

Widder has worked on it for a decade with no grant money and little help. Two years ago, she built a prototype and used a remote undersea vehicle to install it 6,400 feet deep in Monterey Canyon off the California coast. When she hauled it up, the case was flooded. "Success in life depends on how well you handle Plan B," she says. "Anybody can handle Plan A."

Plan B was to fix the leak and try again. This time she got pictures. At first, she was pleased. The fish didn't startle when the light came on, and she assumed they hadn't spotted it. But when she studied the film more carefully, she saw that when the light came on, the fish began to move away. So this year it's on to Plan C. She has no intention of failing to capture "the best light show on the planet" faithfully and unobtrusively. "We know so little about these animals," she says. "I'm very interested to see what these bizarre displays are about, these totally bizarre behaviors we just don't understand yet."