Mystery of the dark solitons

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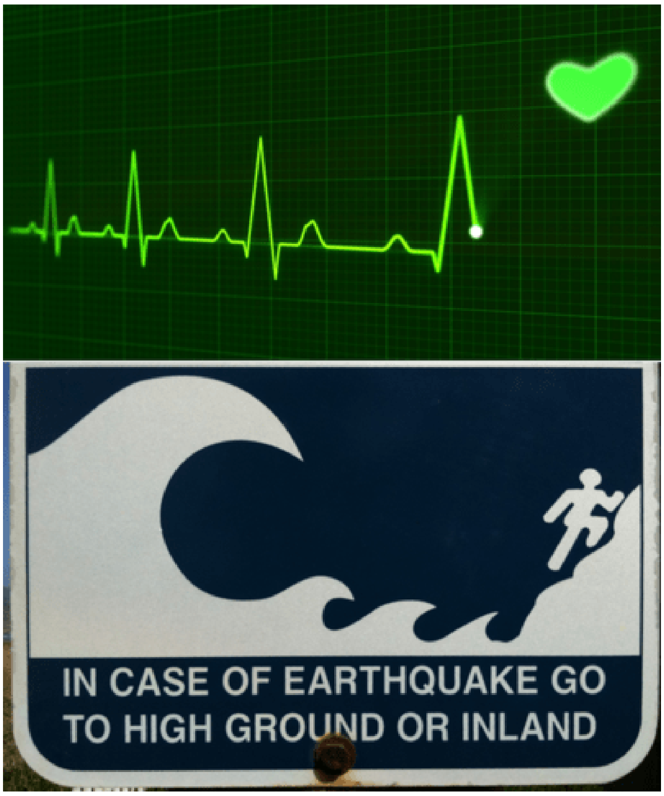

Solitons are common in the natural world. Your pulse is a soliton, and soliton theory may also explain the behavior of tsunamis. Credit: National Institute of Standards and Technology

When your heart beats, blood courses through your arteries in waves of pressure. These pressure waves manifest as your pulse, a regular rhythm unperturbed by the complex internal structure of the body. Scientists call such robust waves solitons, and in many ways they behave more like discrete particles than waves. Soliton theory may aid in the understanding of tsunamis, which—unlike other water waves—can sustain themselves over vast oceanic distances.

Solitons can arise in the quantum world as well. At most temperatures, gas atoms bounce around like billiard balls, colliding with each other and rocketing off into random directions, following the rules of classical physics. Near absolute zero, however, certain kinds of atoms suddenly start behaving according to the very different rules of quantum mechanics, and begin a kind of coordinated dance. Under pristine conditions, solitons can emerge inside these ultracold quantum fluids, surviving for several seconds.

Curious about how solitons behave in less than pristine conditions, scientists at NIST's Physical Measurement Laboratory, in collaboration with researchers at the Joint Quantum Institute (JQI), have added some stress to a soliton's life. They began by cooling down a cloud of rubidium atoms. Right before the gas could take on uniform properties and become a homogenous quantum fluid, a radio-frequency magnetic field coaxed a handful of these atoms into retaining their classical, billiard ball-like state. Those atoms are, in effect, "impurities" in the atomic mix. The scientists then used laser light to push apart atoms in one region of the fluid, creating a solitary wave of low density—a "dark" soliton.

In the absence of impurities, this low-density region stably pulses through the ultracold fluid. But when atomic impurities are present, the dark soliton behaves as if it were a heavy particle, with lightweight impurity atoms bouncing off of it. These collisions make the dark soliton's movement more random. This effect is reminiscent of Einstein's 1905 predictions about randomized particle movement, dubbed Brownian motion.

Artist's impression of a dark soliton, the dip in the center, surrounded by clouds of white impurity atoms. Credit: E. Edwards/JQI

Guided by this framework, the scientists also expected the impurities to act like friction and slow down the soliton. But surprisingly, dark solitons do not completely follow Einstein's rules. Instead of dragging down the soliton, collisions accelerated it to a point of destabilization. The soliton's speed limit is set by the speed of sound in the quantum fluid, and upon exceeding that limit it exploded into a puff of sound waves.

This behavior made sense only after researchers changed their mathematical perspective and remembered to treat the soliton as though it has a negative mass. This is a quirky phenomenon that arises for certain collective behaviors of many-particle systems. Here the negative mass is manifested by the soliton's darkness—it is a dip in the quantum fluid rather than a tall tsunami-like pulse. Particles with negative mass respond to friction forces opposite to their ordinary cousins, speeding up instead of slowing down.

"All those assumptions about Brownian motion ended up going out the window. None of it applied," says Hilary Hurst, a graduate student at JQI and lead theorist on the paper. "But at the end we had a theory that described this behavior very well, which is really nice."

Lauren Aycock, lead author on the paper, lauded what she saw as particularly strong feedback between theory and experiment, adding that "it's satisfying to have this kind of successful collaboration, where measurement informs theory, which then explains experimental results."

Solitons in the land of ultracold atoms are intriguing, say Aycock and Hurst, because they are as close as you can get to observing the interface between quantum effects and the ordinary physics of everyday life. Experiments like this may help answer a deep physics riddle: where is the boundary between classical and quantum? In addition, this result may cast light on a similar problem with solitons in optical fibers, where random noise can disrupt the precise timing needed for communication over long distances.

Provided by National Institute of Standards and Technology

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