Solitons: A Universal Phenomenon of Self-Trapped Wave Packets

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More than 150 years have passed since solitons were first observed by J.S. Russell in the water of a shallow canal in Scotland. In the most general sense, solitons are self-trapped, localized, wave packets that do not broaden while propagating in a dispersive environment. Solitons exist by virtue of the balance between the dispersion (or diffraction) that tends to expand the localized wave packet, and the nonlinear effect that tends to localize it. This characteristic is unique in its own right: it implies that through the nonlinear effect, the wave packet simultaneously induces a potential well and captures itself in its own induced potential. Even more fascinating, solitons propagate and interact with one another, while displaying properties normally associated with real particles: hence the name "solitons."

Russell's observation drew little attention at the time. It was not until the latter part of the 20th century that the field of solitons and nonlinear science in general began to flourish. In recent decades, solitons have been identified in a number of different physical systems:

- shallow- and deep-water waves;
- charge-density waves in plasmas;
- sound waves in liquid ^{3}He;
- matter waves in Bose-Einstein condensates;
- excitations on DNA chains;
- "branes" at the end of open strings in superstring theory; and
- domain walls in supergravity, to name only a few.

Solitons of electromagnetic waves were even identified in an absolute vacuum (in this case they were supported by quantum electro-dynamic nonlinearities). The largest variety of soliton manifestations, however, is in optics. In all these highly diverse systems, which may vary in aspects ranging from size and dimension to forces and physical mechanisms, solitons exhibit features that are practically universal: they are all self-trapped entities possessing particle-like behavior.

Most researchers agree that optical solitons are at the forefront of soliton research in all the branches of science in which solitons are studied. Why did this happen? One important reason is the optical-communication technology boom of the past decade. During this period, the need for high-capacity optical transmission and electro-optical and all-optical processing of information has led to large investments of resources in nonlinear optics research. Another reason is that the necessary technology has matured: powerful lasers are now less expensive and more reliable, monitoring and sampling technology for ultrafast optics is readily available, and material science for fabricating complex photonic structures has made significant progress. But there is more to it than that. The beauty of optics is that it allows one to study a variety of highly nonlinear effects directly, visualizing every detail of the physics involved and isolating the underlying effects.

Reenactment of J.S. Russell's mid-19th century sighting of a soliton wave in a shallow water canal in Scotland. The single isolated water wave traveling in front of the boat is the soliton. Without the nonlinear action, an isolated water wave would broaden within a very short propagation distance. Here the boat generated the wave, which became an independent entity: a soliton.

The fact that solitons in so many systems in nature exhibit universal features raises a provocative question: could there be more to it? Is it possible that God does not play with dice, but with solitons? Such conjectures, apart from being an "improvisation" on a statement made by Albert Einstein to provoke supporters of then nascent quantum mechanics theory, may actually contain merit. If quantum mechanics could include nonlinear terms, even very small corrections, then such effects could potentially lead to self-localization of the wave functions. Perhaps—just perhaps—this would help the next generation of scientists explain and overcome some of the peculiarities of today's quantum mechanics. Of course, adding nonlinear corrections to quantum mechanics is far from being a trivial challenge.[1] But that's not the whole story. It turns out that self-localization experiments with matter waves (neutrons) were actually performed, some 20 years ago,[2] but showed no indications whatsoever of nonlinear effects. All subsequent experiments attempting to measure the effects of nonlinear correction terms to quantum mechanics have shown negative results.[3] So the question of why soliton phenomena are so universal remains unanswered.

In the meantime, we stay with the beautiful physics of solitons, and keep wondering about the origins of this fascinating universal phenomenon. In this issue of OPN, we have worked to bring together an engaging collection of review articles on optical solitons and to provide the optics community with a glimpse of the most exciting highlights of optical soliton research. I read each article in this issue with pleasure. And now, I wish you all enjoyable reading!

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