Behavior of turbulent flow of superfluids is opposite that of ordinary fluids

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A superfluid moves like a completely frictionless liquid, seemingly able to propel itself without any hindrance from gravity or surface tension. The physics underlying these materials—which appear to defy the conventional laws of physics—has fascinated scientists for decades.

Think of the assassin T-1000 in the movie "Terminator 2: Judgment Day"—a robotic shape-shifter made of liquid metal. Or better yet, consider a real-world example: liquid helium. When cooled to extremely low temperatures, helium exhibits behavior that is otherwise impossible in ordinary fluids. For instance, the superfluid can squeeze through pores as small as a molecule, and climb up and over the walls of a glass. It can even remain in motion years after a centrifuge containing it has stopped spinning.

Now physicists at MIT have come up with a method to mathematically describe the behavior of superfluids—in particular, the turbulent flows within superfluids. They publish their results this week in the journal *Science*.

"Turbulence provides a fascinating window into the dynamics of a superfluid," says Allan Adams, an associate professor of physics at MIT. "Imagine pouring milk into a cup of tea. As soon as the milk hits the tea, it flares out into whirls and eddies, which stretch and split into filigree. Understanding this complicated, roiling turbulent state is one of the great challenges of fluid dynamics. When it comes to superfluids, whose detailed dynamics depend on quantum mechanics, the problem of turbulence is an even tougher nut to crack."

To describe the underlying physics of a superfluid's turbulence, Adams and his colleagues drew comparisons with the physics governing black holes. At first glance, black holes—extremely dense, gravitationally intense objects that pull in surrounding matter and light—may not appear to behave like a fluid. But the MIT researchers translated the physics of black holes to that of superfluid turbulence, using a technique called holographic duality.

Consider, for example, a holographic image on a magazine cover. The data, or pixels, in the image exist on a flat surface, but can appear three-dimensional when viewed from certain angles. An engineer could conceivably build an actual 3-D replica based on the information, or dimensions, found in the 2-D hologram.

"If you take that analogy one step further, in a certain sense you can regard various quantum theories as being a holographic image of a world with one extra dimension," says Paul Chesler, a postdoc in MIT's Department of Physics.

Taking this cosmic line of reasoning, Adams, Chesler and colleagues used holographic duality as a "dictionary" to translate the very well-characterized physics of black holes to the physics of superfluid turbulence.

To the researchers' surprise, their calculations showed that turbulent flows of a class of superfluids on a flat surface behave not like those of ordinary fluids in 2-D, but more like 3-D fluids, which morph from relatively uniform, large structures to smaller and smaller structures. The result is much like cigarette smoke: From a burning tip, smoke unfurls in a single stream that quickly disperses into smaller and smaller eddies. Physicists refer to this phenomenon as an "energy cascade."

"For superfluids, whether such energy cascades exist is an open question," says Hong Liu, an associate professor of physics at MIT. "People have been making all kinds of claims, but there hasn't been any smoking-gun type of evidence that such a cascade exists. In a class of superfluids, we produced very convincing evidence for the direction of this kind of flow, which would otherwise be very hard to obtain. "

The power of duality

Holographic duality is a mathematical principle first proposed in 1997 by physicist Juan Maldacena. The theory can be described by envisioning a theoretical lake that's split into two layers: an overlying 2-D surface and a 3-D interior. Maldacena's theory posits that on the lake's surface, there is no gravity—an environment that can best be described by particle theory. On the other hand, the underlying interior is thought to consist of tiny strings that vibrate, fuse and break apart to create matter and gravity—an environment that can be mathematically explained by string theory.

Maldacena's theory of holographic duality demonstrates that behaviors within the gravity-bound 3-D interior can be mathematically translated into behaviors on the zero-gravity 2-D surface.

Liu and his colleagues applied equations of holographic duality to the physics of black holes—objects that are bound by extreme gravitational forces—and translated these forces to the behavior of zero-gravity superfluid turbulence, which is otherwise considered incredibly difficult to characterize.

"The power of this duality is that difficult questions on one side can become much easier on the other side," Liu says.

To make an accurate translation, the researchers first looked for a black hole whose surrounding matter would resemble the random turbulence of a superfluid. They eventually settled on a type of black hole surrounded by a chaotic swirl of matter and electromagnetism.

The researchers studied the complex physics of this particular type of black hole, solving equations to characterize its behavior. They then applied models of holographic duality to translate the black hole's physics to the turbulent flows of superfluids.

"It's like there exists a decoder ring that takes information about a black hole and maps it onto information about fluid mechanics," Chesler says.

From the cosmos to fluid mechanics

Through their calculations, the researchers were able to characterize how energy flows through a superfluid in turbulent flows. In ordinary fluids, energy flows differently depending on whether the fluid is flowing on a flat 2-D surface or in a deeper body, such as a river. Scientists have previously found that 2-D liquids tend to start out as relatively small structures, but as they flow, their energy combines to form larger and larger structures—similar to the way tornadoes can merge to form hurricanes.

In contrast, liquids in 3-D behave in the opposite manner, starting as large structures and spinning out into smaller structures, much like the dispersal of cigarette smoke.

In the case of superfluids, Chesler and his colleagues found that in 2-D, superfluids behave unlike ordinary fluids in 2-D, but more like ordinary fluids in 3-D, dispersing energy at smaller and smaller scales.

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