
D. ALLISON

COSMOS IN A BOTTLE

Physicists often borrow techniques from other fields. But how far can this get you? **Geoff Brumfiel** asks if simple table-top experiments can provide new insights into the early Universe.

Take a look at water running in a sink and you'll see an intriguing everyday phenomenon. As water from the faucet strikes the basin, it will create a small saucer of moving water. The water entering this saucer from above flows smoothly and radially out; its even flow creates a ring of ripples which holds the more turbulent water in the rest of the sink at bay. Outside the ring, the water is full of waves and eddies, but on the inside, the water is moving out too fast for the ripples to penetrate — no information from the rest of the sink can cross into the circle.

One of the long term goals of the astronomical community is to produce images of the 'event horizons' that surround black holes — the ultimate points, or rather surfaces, of no return. Theoretical physicists have spent decades calculating what happens at event horizons, and astronomers now want to spend decades more, and billions of dollars, trying to see what one actually looks like. However, other physicists think that they can get at least some of the answers to that question by studying those rippling fluid rims in the sink.

The analogy between sink-saucer and black hole isn't perfect. For one thing, water flows out from the horizon line into the sink, while quite the reverse happens in a black hole. But according to Bill Unruh, a theoretical physicist at the University of British Columbia in Vancouver, Canada, it is closer than you might think. In the early 1980s Unruh imagined a similar sort of flow as a thought experiment: a waterfall in which the falling water exceeded the speed at which sound waves could travel in the fluid[1]. In that system it is the point when water reaches the speed of sound that creates an 'event horizon' beyond which sound can never escape. "If you set up the flow right," he says, "you could exactly mimic a black hole."

Getting the flow right

Since that time, a small coterie of physicists has devoted itself to simulations of esoteric phenomena such as black holes and the workings of the early Universe. But before anyone starts to think about saving billions of space-faring dollars with some cleverness in the kitchen sink, there are a few caveats. Getting "the flow right", as Unruh puts it, tends to mean using superfluid liquid helium only a fraction of a degree above absolute zero, or some even more esoteric system, such as a set of ultracool trapped atoms in a Bose–Einstein condensate — another close-to-absolute-zero fluid with quantum properties. Most of the proposed setups haven't even made it off the drawing board; only a handful of experiments have been successfully carried out.

And then there's the problem of what, if anything, such models actually tell you. If system B mimics system A in a set number of ways, and goes on to exhibit some other hitherto unlooked for activity, does that mean that system A does the same thing? Or does it mean that the two systems are not that similar after all?

Despite these worries, kitchen-sink or table-top cosmology continues to generate excitement among a small but fervent group of physicists, mostly in Europe, where there is a small but steady stream of funding for such research. Much of the work involves superfluid helium, a good medium for studying phase transitions — transitions from one state to another — and quantum effects, both subjects of great importance in cosmology. Later this month, those interested in condensed matter and cosmology will gather at the Royal Society in London to discuss the future of their attempts to mimic — and manipulate — the otherwise unobservable. "You're never going to do experiments *in situ*," says Tanmay Vachaspati, a cosmologist at Case Western Reserve University in Cleveland, Ohio. "It has to be in a laboratory setting."

Cosmic inflation

The field of condensed matter, which covers everything from waterfalls to semiconductors, has always been a useful source of inspiration for those interested in the origin of the cosmos, according to Paul Steinhardt, a cosmologist at Princeton University in New Jersey. In the mid-1980s, he was working on refining a theory known as cosmic inflation that postulates that the Universe underwent a period of extremely rapid expansion shortly after the Big Bang. The problem at the time, Steinhardt says, is that nobody knew how to explain how the transition from inflation to today's more slowly expanding Universe occurred. The dominant thinking then was that the present day Universe would have begun as bubbles in the inflationary cosmos. But the bubbles, according to calculations, would be nothing but vacuums — matter and energy would never have developed under such conditions.

Steinhardt himself was stuck until he read a description of unusual 'phase transitions' in a mixture of helium isotopes. Normal fluids change their phase — from gas to liquid, say — following a bubble regime similar to the one that theorists believed ended inflation. But the mixture of superfluid helium changed its properties in a completely smooth, uniform fashion. Applied to cosmology, the superfluid transition allowed the entire Universe to gently roll from inflation to the present-day conditions, says Steinhardt.

Since Steinhardt's work, superfluid helium has emerged as the material of choice in these sorts of experiments. In particular, helium-3, an isotope of helium with two protons and one neutron, has very unusual properties, which make it an unusually good proxy for the cosmos.

In addition to exotic phase transitions, helium-3 can undergo the phenomenon of 'symmetry breaking'. Normally, pairs of atoms in the liquid have their spin and orbital angular momentums aligned in random directions. But when cooled, the helium atoms will snap into a single alignment. The process is somewhat like iron filings lining up in a magnetic field, except that the helium arranges itself spontaneously — creating order from chaos. Physicists believe that symmetry breaking in the early Universe led to the creation of every force except gravity.

Taken together, the symmetries and phases of a helium-3 superfluid give the quantum liquid an important Universe-like quality, says Grisha Volovik, a condensed-matter theorist at the Helsinki University of Technology in Finland. "All the ingredients are certainly there," he says.

So how far can such analogies can be trusted? And what if the cosmological theories being tested are themselves wrong? Around the time at which Steinhardt was refining his inflation theory, a theoretical physicist at Imperial College in London, Tom Kibble, was working on an alternative model. Kibble had a theory that the cooling of the early Universe as it expanded also created massive structural defects — called cosmic strings — that were the seeds of the large network of galaxies we see today.

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Kibble's hypothesis worked perfectly in helium-3, where rapid cooling led to a tangle of 'quantum vortices' that matched his theory. Unfortunately, he says, his cosmic strings theory of galactic structure failed to match up with astronomical observations of the cosmic background radiation left over from the Big Bang. After satellites designed to study the cosmic background delivered their results in the early 1990s, Kibble says: "It became clear that the predictions of inflation were rather good, and the predictions of cosmic strings were completely wrong."

In other words, laboratory models had verified the theorists' equations, but they had provided absolutely no insight into whether those equations could be applied to the cosmos.

That early failure left many experimentalists and theorists sceptical of any bench-top models of the early Universe. "Frankly," says Wolfgang Ketterle, a Nobel-Prize-winning condensed-matter physicist at the Massachusetts Institute of Technology in Cambridge, "I don't think a table-top experiment will answer fundamental questions about the cosmos any time soon."

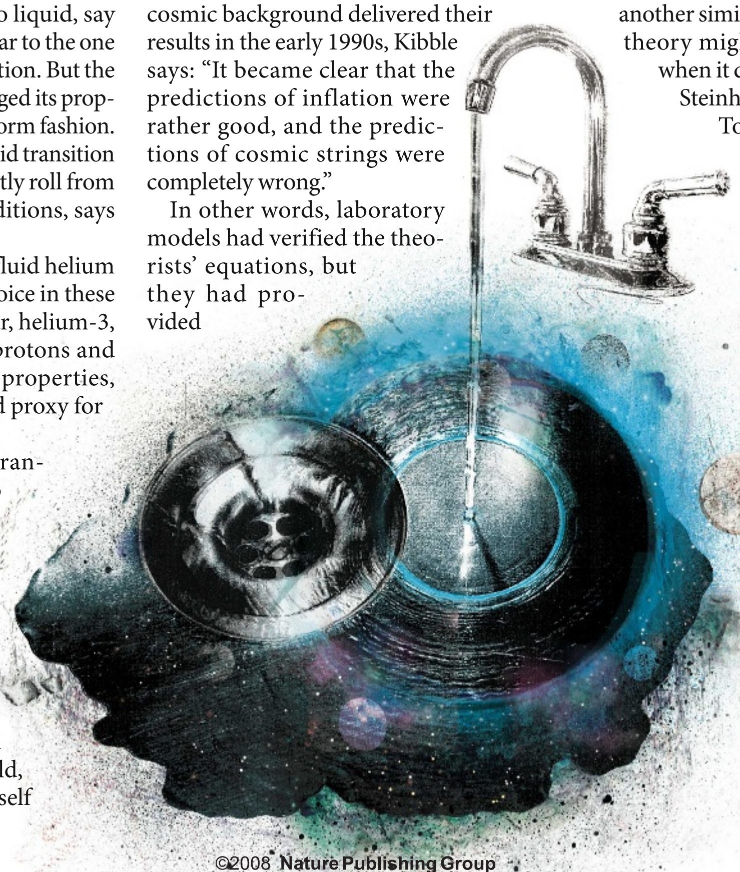
Stringing it together

Such concerns have not stopped Richard Haley of Lancaster University, UK, from pursuing lab analogues for string theory — perhaps the most experimentally intractable theory of fundamental physics. String theory is controversial because it has evolved over the past two decades almost without reference to experiments or observations, and so some critics view it more as a branch of mathematics than of physics.

Some versions of string theory postulate that our Universe may sit on a three-dimensional membrane, or 'brane', suspended in a higher-dimensional space, the way a two-dimensional sheet of paper sits in the three-dimensional world. In such models, string theory explains the end of the inflationary period through the collision of our brane with another similar brane. If it were true, the brane theory might explain why inflation ended when it did, a question left unanswered by Steinhardt's earlier work.

To create colliding branes in the lab, Haley brought two phases of helium-3 together. His team used a magnetic field to create a helium-3 sandwich, with one part of the superfluid, the A-phase, as the filling and the other, the B-phase, as the bread. They then decreased the field strength and watched as the two B-phases collided[2]. Mathematically speaking, Haley says, the phases are good analogies for cosmic branes.

In Haley's experiment the colliding phases did not merge smoothly into one uniform B-phase, but instead left behind structural defects — most likely quantum vortices of the same sort predicted by Kibble. If these swirling vortices have analogies in the Universe,



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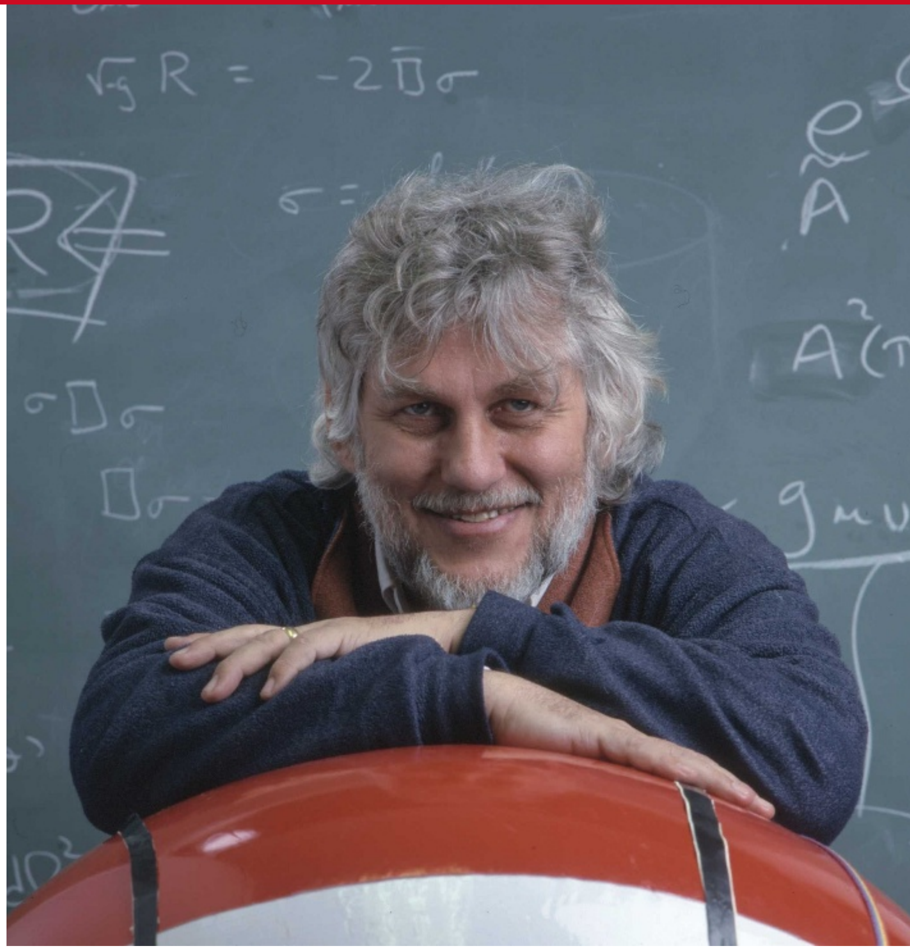
then they should be detectable as massive cosmic strings. Unlike Kibble's original idea, these strings would be a smaller fraction of the Universe's mass, but they should still be detectable by using ground and space-based interferometers to observe gravitational waves. Haley, meanwhile, says that he and his team are now working to further understand the different kinds of vortices created by the collision.

Testing the untestable

Of course, cosmologists need to apply caution when interpreting such lab-based results. Steinhardt notes that string branes are flat and attract one another, whereas the helium-3 'branes' are curved and have no attractive force. The model is far from perfect. Still, in a field such as string theory where exotic mathematics reigns supreme, an experiment that makes any testable prediction could have a big impact, says Joe Polchinski, a string theorist at the Kavli Institute for Theoretical Physics in Santa Barbara, California. "You never know what you might find," he says.

From the experimentalist's perspective, even a failed analogy can find another purpose. The quantum vortices first predicted by Kibble and his colleague Wojciech Zurek, a quantum theorist at the Los Alamos National Laboratory in New Mexico, are now being used to track the movement of helium-3 in other experiments, according to Matti Krusius of Helsinki University of Technology. "This is a nice phenomenon," he says. "We use it to study turbulence."



Bill Unruh hopes that experiments will mimic the behaviour of a black hole in the laboratory.

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Such crossover from cosmology into condensed matter is a common and overlooked benefit of these collaborations, says Ralf Schützhold, a quantum theorist at the Technical University of Dresden in Germany. Because the Universe has been expanding since the time of the Big Bang, cosmologists' equations that model this expansion can work well for systems that are changing. That makes them particularly useful for understanding phase transitions and other phenomenon. "It's very nice to consider effects in condensed matter based on these beautiful equations from cosmology," he says.

Schützhold and his team are now working on a different cosmological analogue that could help to explain the origin of matter and energy in the Universe. Under normal circumstances, atoms are constantly moving, but when a single atom is chilled to near absolute zero, its real motion converts into 'virtual' quantum fluctuations, which are temporary changes in the amount of energy in a small volume of space. Following inflation, cosmologists believe that the Universe underwent the reverse of that process: virtual quantum fluctuations in the vacuum of space became real matter and energy. A laboratory experiment on a single atom, Schützhold says, could allow him and others to see how thermal noise and other real-world effects altered the fluctuations that created the cosmos we see today.

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Good vibrations

Controlling a single atom is no small task, but Tobias Schätz, Schützhold's experimental partner at the Max Planck Institute for Quantum Optics in Garching, Germany, says that he is reasonably confident that it can be made to work. Even if it can't, he says, the project is likely to aid his work in quantum computing. "We have to work in this direction anyway," says Schätz.

That's just as well, because experiments to realize the quantum vibrations of an atom require exquisite control of the laser system used to cool it. "It is really pushing experimental technique to its limits," says Ketterle. Basing a career on such analogies would be "scientific suicide", he says, especially given their tentative link to actual cosmology.

Experiments on the black-hole models that Unruh first described are even further off. Efforts to create a waterfall equivalent in helium-3 have been stymied by fluid turbulence. Other approaches are now in the works: some groups are working with Bose–Einstein condensates[3], which can be studied at lower flow speeds than helium-3. Other techniques employ a series of light pulses in special fibre-optic cables[4].

Ultimately, a lab analogue that displays quantum behaviour is needed. Such a system could allow experimentalists to observe Hawking radiation — a quantum-mechanically induced glow that theorists predict exists around the event horizon. The pay-off for theorists in this case promises to be tangible: an observation of Hawking radiation in such a system could inform debate about whether and how black holes 'evaporate' over time.

So despite nearly two decades of waiting for his black-hole analogy to reach fruition, Unruh's enthusiasm for the project remains undimmed. "It's a really neat idea and it would be great if it works," he says, then adds: "I'm astonished every time I see what these experimentalists can do." ■

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