# The Splintered Universe

## Physicists model the early universe in droplets of superfluid helium

By DAN VERGANO

If there were a cosmic complaints department that honored warranties on the Big Bang, the universe would have been returned shortly after it exploded into existence. Most physicists believe that the primordial fireball shuddered through several breakdowns within the very first moments of time. These collapses may have splintered the young universe, riddling it with defects.

One might argue that this is just the sort of thing that discourages big consumer purchases, but some cosmologists contend we're lucky to have had cracks in creation. Without matter clumping together in the wake of these cosmic defects, no stars would have formed (SN: 3/24/90, p. 184). Without stars, there would have been no Earth. No Earth, no earthlings.

A neat theory, but proving it presents a large obstacle, says one of its originators, Thomas W. B. Kibble of Imperial College in London. "Obviously, the problem with the early universe is you can't do experiments on it."

Twelve years ago, however, one physicist proposed a novel method of modeling the early universe in the laboratory. Several teams have now applied his scheme and are drawing lessons about what may have happened immediately after the Big Bang.

Wojciech H. Zurek's idea for recreating the early universe grew out of his eavesdropping at an interdisciplinary physics meeting in 1984. "I was listening to people talk about Big Bang cosmology. I didn't understand what they were saying," recalls Zurek, a physicist at the Los Alamos (N.M.) National Laboratory.

The cosmologists were puzzling over the aftermath of the Big Bang. Following the initial explosion, they asked, why wasn't the sky paved with smoothly distributed hydrogen? How did galaxies come together in the first place, and what herded them into grouped clusters (SN: 9/23/95, p. 202)?

Zurek read halfway through one of Kibble's papers, and he began to understand: The cosmologists were saying that as the early universe cooled, it went through phase transitions.

As a condensed-matter physicist, he had studied these phenomena. They occur when matter suddenly changes its structure because of alterations in the pressure or temperature around it, such as when water freezes into ice.

Yuri Bunkov/Grenoble

*This Grenoble apparatus set a low-temperature record.*

Where there are phase transitions, there are often defects. Just as cracks frequently appear in ice cubes as they form, so flaws sprang up in the early universe. According to cosmological theory, these imperfections were whirlpools of primordial matter that spun off at moments of cosmic transition. Alongside other oddly shaped blemishes, the vortices would have spanned the length of the early universe with a distorting mass whose gravity pulled nearby matter into its fast-moving trail.

Voila, clumps of galaxies.

Zurek didn't finish the paper. Instead, he began thinking about the way whirlpools, or vortices, spread through fluids and how to model these whirlpools in the laboratory.

Publishing his ideas in 1985, he first suggested that researchers mimic the vast emptiness of space by using a superfluid—an extremely cold liquid that lacks friction. Like the interstellar void, superfluids offer no resistance to motion (SN: 4/9/94, p. 239). A canoe paddle dipped into a superfluid pond would fail to move the boat.

Next, he suggested that when superfluid helium undergoes a phase transition to form liquid helium, vortices would spring up, just as spiraling defects erupted in the decay of the Big Bang. Physicists studying these eddies would, in essence, watch a replay of the early universe.

In 1985, a group of physicists at Los Alamos began trying Zurek's proposed experiment with liquid helium-4, a heavy isotope of the element. They found that lowering the substance to superfluid temperatures—a few degrees above absolute zero—while looking for tiny defects in the liquid was beyond their ability. When one of the group's leaders died in 1987, the effort ended.

"Since no one was doing these experiments, I thought I'd give it a go," says Bernard Yurke of Lucent Bell Laboratories in Murray Hill, N.J. (SN: 6/1/91, p. 344). In 1991, he and theorist Neil Turok of Princeton University modeled cosmic defects by using liquid crystals, the orderly liquids that line up to form numerals in digital watches.

The molecules of liquid crystals can undergo a phase transition that causes them to line up in one direction. When Yurke triggered such a transition by abruptly increasing the pressure on the liquid crystals, he observed alignments in several locations at once, all pointing in different directions. All sorts of defects sprang up at the intersections of these liquid crystal lines. Vortices whirled apart and then rejoined. Pulsating dots appeared and then annihilated one another. Curious, knotlike flaws rippled for a time and then faded.

The researchers observed more than 20 defects in the liquid crystals. "How the defects move mimics what may have happened at early times," says Yurke.

Although this experiment did not include the frictionless environment of a superfluid, it had two advantages: The vortices could be observed through a microscope rather than a nuclear magnetic resonance imaging instrument, and their phase transition took place at room temperature. "It's a marvelous idea," says Zurek, who is excited that these early tests supported at least part of his theory.

Meanwhile, Peter McClintock of the University of Lancaster in England had read Zurek's original paper and become fascinated by the idea of modeling the early universe in a superfluid. He decided against trying it "because I thought somebody is bound to do it in 6 months. And then nobody did, so I thought, perhaps we'll have a go at it," he says.

In 1994, his group finally carried out Zurek's original suggestion by using helium-4 to study analogs of cosmic defects. The physicists placed a milligram of liquid helium inside a bronze bellows cooled to 2°C above absolute zero. Expanding the bellows, they induced a pressure drop in the helium that caused it to shift to a superfluid state. At the same time, the investigators fired sound waves into the helium.

Unable to look directly at the invisible vortices, they relied upon distortions in the movement of the sound waves to reveal the swirls. The results verified Zurek's predictions. "We showed you get enormous defects after transition," says McClintock.

It's not so outlandish to use a drop of liquid helium to model the entire universe, McClintock explains. According to theory, cosmic defects developed $10^{34}$ seconds after the Big Bang sprang forth from an infinitesimally small point. "At the time we're talking about, the universe was very small—perhaps the size of a golf ball," says McClintock.

Despite the success of the experiment, superfluid helium-4 frustrated researchers because they could not peer directly at vortices. They began eyeing the other helium isotope, helium-3, whose atomic nuclei spin in such a way that the substance is readily visible to nuclear magnetic resonance imaging instruments. Experimental physicists had avoided the isotope heretofore because it turns into a superfluid at only a few tenths of a degree above absolute zero, making it very difficult to handle.

One exciting feature of helium-3 is that it absorbs neutrons, says Kibble. Working at the Helsinki University of Technology in Finland, he and physicists from Europe and the United States fired neutrons into superfluid helium-3 contained in a 5-millimeter-wide cylinder. With each heat-producing impact, small pockets of normal fluid bloomed in the frictionless reservoir. As the liquid cooled back down to superfluid status, the researchers observed cigar-shaped vortices in the remnants of the pockets.

By rotating their apparatus, the researchers lured these defects into the center of the cylinder long enough to count them. In the July 25 NATURE, the team reported finding the same number of vortices Zurek had predicted in 1985.

That issue of NATURE also contained an experiment that complemented and extended the Helsinki study. Researchers at the Center for Very Low Temperature Research in Grenoble, France, cooled superfluid helium-3 to 160 millionths of a degree above absolute zero. At this temperature, vortices stabilized as soon as they formed.

Lacking nuclear magnetic resonance imaging equipment, the second group rigged a system of sensitive wires within the superfluid and then shot a neutron of known energy into the chamber. By looking at how much energy the fluid absorbed, the physicists from Grenoble and Lancaster could determine the strength of the resulting vortices. The two helium-3 experiments, like McClintock's, agreed with Zurek's prediction.

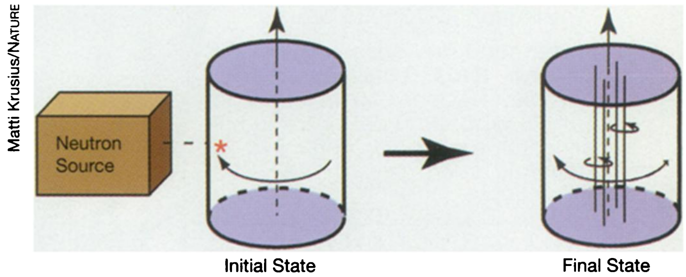
"The fact that we have three experiments in superfluids, with totally different ways of doing effectively the same thing, is nice because it's added confirmation," says Alasdair Gill of the University of Geneva, who participated in the Helsinki experiment.

Dimitri Nanopoulos, a physicist at Texas A&M University in College Station, cautions that the studies test only a model, not the actual early universe. Still, he calls the experiments "a remarkable achievement."

If cosmic defects existed just after the Big Bang, the recent studies could shed some light on them. These strange beasts would have roared through the universe as extraordinarily thin, dense strings $10^{31}$ meters in diameter. Each meter of their length would have weighed $10^{19}$ kilograms and had a huge gravitational pull. "If you were to have one go down the street, you'd see the houses on both sides pull in behind it at something close to the speed of light," says Gill. Such aggregation of matter in the wake of a cosmic defect's passage is what scientists speculate started the formation of galaxies.

In two of the experiments, the vortices contained viscous liquid helium, trapped at a temperature just above that of the superfluids. These results suggest that cosmic strings preserved remnants of primordial matter, seething at the high temperature of the Big Bang, long after the birth of the universe.

A competing theory of cosmology, called inflation, posits that galaxies grew out of gravitational shock waves in the expanding universe (SN: 5/8/93, p. 296). Gill believes that inflation lost some of its adherents this summer after the helium-3 experiments lent support to the cosmic defects model.




*Sparked by a single neutron, vortices accumulate in the center of the rotating cylinder.*

"It's getting to the stage where it seems very plausible," he says. "You obviously want to push it further—to know not just how many vortices or cosmic strings there were, but also if they are all in loops or long, straight strings. You want to know all the patterns of strings."

Astronomers are starting to study photographs of stars, searching for distinctive gravitational effects caused by cosmic strings.

To settle the argument between inflation and cosmic strings, many physicists await studies of the cosmic background radiation—heat left over from the Big Bang. Finding uneven radiation would argue for the cosmic defect theory. Current studies measure only slices of sky more than 10° across, not fine enough to decide the issue.

Until physicists build instruments capable of resolving the background radiation in fine detail, they will have to content themselves with recreating the universe in liquid helium. Zurek sees a benefit to bringing together cosmology and low-temperature physics—the two fields enrich each other's perspective.

"The interesting thing is that people saw masses of vortex lines in liquid helium for years and wanted to get rid of them," says Zurek. "We only got to ask questions about them by thinking about cosmology." □