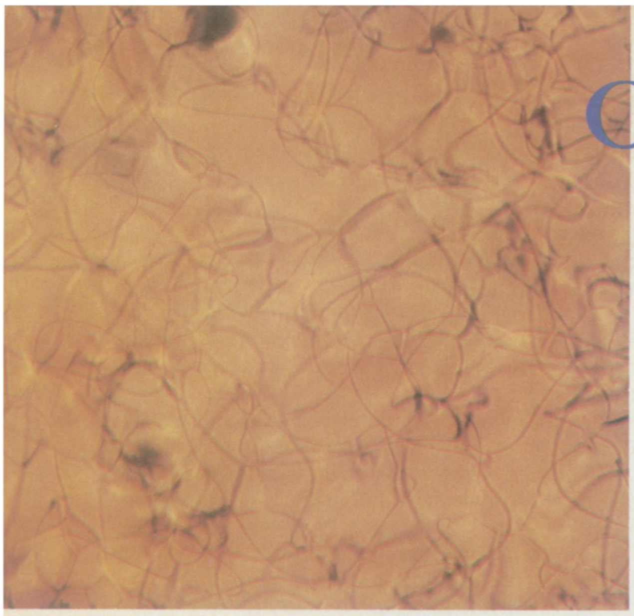


Cracks in the Cosmos

Reflections of the universe in a liquid crystal puddle

By IVARS PETERSON

Cosmologists tend to view the universe through the lens of mathematics. To obtain hints of how the cosmos evolved to its present state, they manipulate and solve equations that purportedly represent conditions during the earliest moments of the universe.

From this abstract mathematical stew, they extract a mess of exotic geometric structures – cosmic strings, monopoles, domain walls, global texture – that rumple the smooth distribution of matter and energy in the universe. They develop intricate scenarios linking these hypothetical primordial "defects" to the huge clusters and lengthy strands of galaxies apparent today.

But unbounded speculation, no matter how deeply rooted in mathematics and physical theory, has its drawbacks. "There's no way to check the ideas," says cosmologist Neil G. Turok of Princeton (N.J.) University. "Even with computer simulations, one's always unsure whether to believe them."

That nagging uncertainty made Turok especially receptive to an unusual proposal set forth last year by Bernard Yurke, an experimental physicist with AT&T Bell Laboratories in Murray Hill, N.J. After pursuing various aspects of quantum optics for more than eight years, Yurke was ready for a change of pace and felt irresistibly drawn to the idea of testing cosmological theories in the laboratory. He developed the notion that tracking the behavior of liquid crystal materials – such as those found in calculator or digital watch displays – could offer insights into the formation and evolution of cosmological defects.

"The [liquid crystal] system is quite analogous to the early universe case," Turok says. "It's a concrete system where you can really test some of the ideas that we have developed for understanding defects in the early universe."

The idea sparked a collaboration between Yurke and Turok, which led to a series of experiments that produced valuable new data for cosmologists, particle physicists and condensed-matter researchers.

"It was a real coming together of three different subjects," Turok says.

Assuming that the universe was once considerably hotter and denser than it is now, cosmologists have long theorized that the breakdown of symmetry during phase transitions accounts for the universe's evolution from a remarkably uniform soup of matter-energy into the structures now visible.

In many ways, this process resembles the freezing of water. As water molecules settle into position to create an ice crystal, they lose their freedom to rotate about an axis or to move in a straight line ("translate") in any direction. In other words, the phase transition from liquid to solid removes, or "breaks," a water molecule's rotational and translational symmetries. Water molecules locked in ice thus show a lower degree of symmetry than do water molecules roaming the liquid.

Even so, phase transitions rarely occur uniformly. When water freezes, the orientation of a crystal formed in one region of the liquid often differs from that of crystals formed elsewhere. This produces a mismatch, or defect, wherever the crystals eventually meet. In ice, such defects show up as milky filaments or frosty sheets suspended in the clear solid.

Theorists postulate that phase transitions involving symmetry-breaking are also responsible for the properties of fundamental particles of matter and account for the development of structure in the universe.

"The standard model of particle physics and all extensions of it are built on the notion of spontaneously broken internal symmetries," Yurke, Turok and their co-workers write in the March 15 Science. "In the standard hot Big Bang cosmology, this automatically leads to defect production as the universe cools through symmetry-breaking phase transitions."

In these instances, the symmetries involve not water molecules or other physical objects but the characteristics of force fields – such as the postulated Higgs field – that govern the behavior of matter. Nonetheless, the mathematical equations describing the diverse types of symmetry-breaking are remarkably similar.

Cosmologists reason that symmetry-breaking phase transitions in the early universe would have left behind an extensive network of interlaced, space-warping defects, which may have served as seeds for galaxy formation. Theoretical arguments present a number of possibilities for the initial distribution and subsequent evolution of this tangle of defects, but they supply no definitive answer (SN: 3/24/90, p.184).

In 1985, noting the close analogy between symmetry-breaking phase transitions in particle and condensed-matter physics, astrophysicist Wojciech H. Zurek of Los Alamos (N.M.) National Laboratory suggested an alternative means of tackling the whole issue. He argued that scientists could gain important insights into the behavior of cosmological defects known as cosmic strings by studying a special kind of vortex defect formed when helium undergoes a phase transition from a normal liquid to a superfluid, which flows without friction.

However, the necessary experiments proved impossible to complete. "The trouble [with helium] is that you have to work at low temperatures, and you have a fairly hard time finding these vortex lines because you can't see them directly," says Zurek.

Yurke, familiar with Zurek's proposal and disappointed that no one had been able to follow up this line of research, took a fresh look at the problem. He proposed tracking the behavior of certain types of liquid crystals, in effect using them as a crystal ball to illuminate the universe's distant past.

"Liquid crystals are fairly simple to deal with," Yurke says. "You don't need a whole lot of technology or expertise — just an optical microscope for observation."

Out of the many different kinds of liquid crystals available, Yurke chose the nematic type, which consists of large, rod-shaped organic molecules. Like molecules in an ordinary liquid, they normally display random orientation. However, lowered temperature or increased pressure induces these molecules to line up parallel to one another. In the transition from a disordered state to a more orderly, aligned phase, the molecules lose some freedom of motion: They can still drift from place to place, but must now maintain a particular orientation.

Yurke, Turok and their co-workers studied a nematic liquid crystal known commercially as K15 or 5CB. In a typical experiment, the substance started out in its molecularly disordered state, appearing as a clear, colorless, featureless liquid ensconced in a transparent cell just a few millimeters wide and only a fraction of a millimeter deep.

By suddenly increasing the pressure on the substance in the cell, the researchers forced a phase transition, which they recorded with a video camera attached to a microscope. The material turned dark, and then an intricate, dense web of spaghetti-like strands gradually penetrated the gloom.

These loops and threads represent mismatches between the orientations of molecules in adjacent sections of the material. "Different patches of the fluid align in different directions, and when they all come together, there are places where conflicts arise that can't be resolved," Yurke explains. Acting like lenses to deflect light, these regions of conflict show up as well-defined strands.

"You can actually see these defects and watch them move," he says.

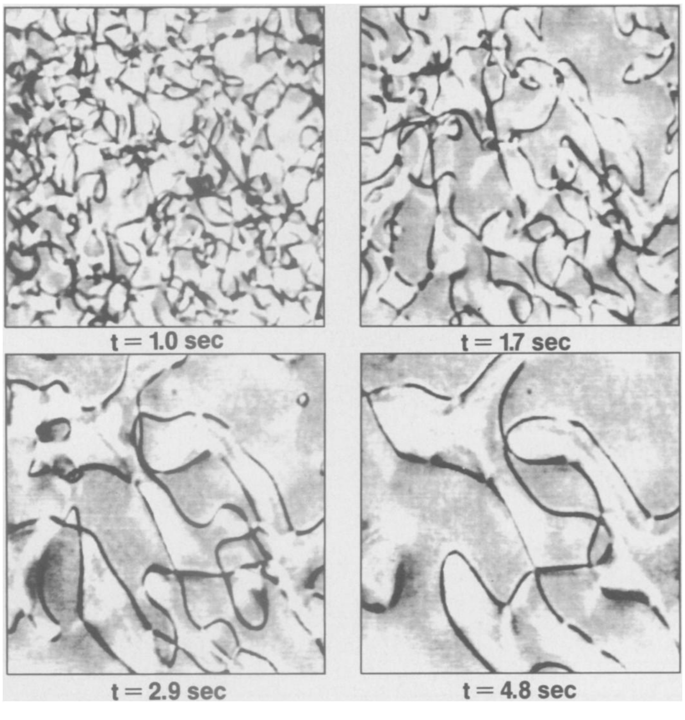
Initially, the tangle of defects is so thick that no light gets through. However, as the defects wiggle about, become shorter and annihilate one another, the material rapidly becomes more transparent.

To identify the defects' geometric structure, Yurke and Turok drew on previous studies in which scientists used polarized light to determine the molecular arrangements responsible for each of the various types of defects found in liquid crystal materials.

"In a nematic liquid crystal," Yurke notes, "you see many line-like defects, which correspond to cosmic strings, and you see a few point-like defects, which are monopoles."

Curiously, the earlier investigations had virtually ignored the ways in which liquid crystal defects changed over time. Yurke and Turok's video images now document the remarkable activity within a defect-ridden nematic liquid crystal, revealing an intricate game of molecular musical chairs. Sharply curved lines straighten out. Constrictions form in the middle of strings. Monopoles and antimonopoles meet to annihilate each other. Long, writhing strings intersect themselves and shed loops, which shrink to single points and then vanish. Sometimes, strings that happen to cross each other snap in two, switch partners and reconnect—an effect often seen in computer simulations of cosmic strings but never before observed in the laboratory, Yurke says.

"We've counted some 20 different kinds of events that take place, and we know that list is incomplete," he says. "An awful lot of things can happen."



A sudden increase in the pressure on a liquid crystal sample induces a phase transition that generates a thick web of strings, which correspond to the boundaries between regions of differently aligned molecules. In a few seconds, the defect tangle thins out and the pattern coarsens. Each picture shows a region about 360 microns wide.

"Every process that we have thought about in the cosmological case actually happens in the [liquid crystal] system," Turok adds.

The experiments also dished up some surprises. For instance, the researchers expected to see the liquid crystal equivalent of a knot-like defect known as texture, but found no convincing evidence of its presence.

"After doing this phase transition several times and never seeing textures, I did a numerical simulation of texture in this substance to see what it would do," Turok says. "Just by accident I noticed that if the texture were slightly asymmetrical, then as the simulation proceeded, the texture actually turned into a monopole-antimonopole pair."

The researchers then returned to their liquid crystal experiments and manufactured a texture defect by hand, using a glass filament, or "whisker," to swirl the fluid. "It sat there for a while, then decayed into a pair of monopoles in just the same way the simulation did," Turok says.

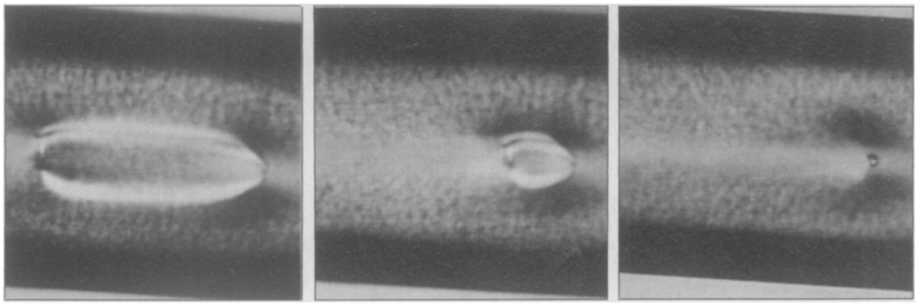
Texture's tendency to decay into monopole pairs, which subsequently annihilate each other, probably accounts for its low profile in a tangle of liquid crystal defects, Turok says. "Nobody expected that this would occur," he notes. "That's the kind of thing that could happen in some cosmological theories."

Observations of the changes that unfold in a liquid crystal — how quickly strings shorten and patterns become more sparse — provide "a very useful check" on cosmological models of large-scale structure formation in the universe, Turok asserts. The new experiments confirm, for example, that a string network evolves in such a way that a thinned-out tangle looks like a magnified version of the original defect tangle. The gaps grow larger, but the overall pattern remains the same.

The liquid crystal system isn't a perfect analog of the cosmological case. Cosmic strings can lash back and forth at nearly the speed of light, for instance, whereas string-like defects in liquid crystals move as if they were immersed in molasses. Researchers comparing the two systems must remember to correct or account for such effects.

But "even though there isn't a one-to-one [correspondence] between the two systems," Yurke says, "you can try out theoretical ideas that you're using on one system and see if they work in the other."

"Best of all," Turok adds, "we can make predictions that can be checked by experiment — normally a rare occurrence these days in cosmology and high-energy physics."



Monopole-antimonopole annihilation in a liquid crystal. In this sequence of photos, two poles — initially 0.4 millimeter apart and apparently joined by a loop — come together over a period spanning 60 seconds.

And there's more to come. To probe other puzzling phenomena, Yurke and Turok are thinking of studying other types of liquid crystals, which have different symmetries and which develop alternative types of defects. By selecting the materials carefully, they hope to find analogs for various mathematical models used to describe the behavior of physical systems.

"I would like to investigate as many of the different symmetry-breakings as I can," Yurke says. "I think that will keep me busy for several years."

Turok wants to learn what liquid crystals can reveal about symmetry-breaking phase transitions in particle physics. In the past year, he says, theorists have shown that a complicated phase transition associated with the electroweak theory — which unites the electromagnetic force with the weak nuclear force responsible for radioactivity — may produce unequal amounts of matter and antimatter. Indeed, this transition, which involves defects generated during bubble formation and growth, may account for the predominance of matter over antimatter in the universe, he suggests.

"It produces roughly the right amount of matter versus antimatter," Turok says. However, "the dynamics of the phase transition are very complicated and hard to understand."

He and Yurke have launched new experiments that may help shed light on that process. Their goal is to observe the motion of the boundary, or "bubble wall," between a liquid crystal partly in the disordered state and partly in the aligned phase. The moving boundary would generate defects, leaving behind a trail of strings.

"This process of producing defects on phase boundary walls is something that has never been studied either in particle theory or in condensed-matter physics," Turok says.

Firsthand observations that strings, monopoles and textures are something more than mathematical entities will prove instructive and revealing to cosmologists, Turok and Yurke maintain. "I had been working with cosmic strings for years, and here I finally got a chance to see them," Turok says. "I'm a strong believer that the real world is a lot more stimulating than the theoretical world."

Scientists in other fields also may gain new inspiration from liquid crystal experiments that focus on the dynamics associated with phase transitions. "These are beautiful experiments," says astrophysicist Zurek. "Just by asking questions relevant to cosmology, you can end up opening a door on a new sort of solid-state physics."

Yurke and his collaborators conclude in SCIENCE: "[We] believe that this is an area in which ... cosmologists, particle physicists and condensed-matter physicists can benefit from increased interaction."

The future looks bright in their liquid crystal ball. ☐