Universe in a Drop
Cosmology in the liquid laboratory

By IVARS PETERSON

Liquid helium chilled to temperatures near absolute zero undergoes a curious transformation. Below 2.172 kelvins, it becomes a superfluid, a state in which the liquid flows without friction.

Such behavior seems to have little in common with the expansion and cooling of an extremely hot universe just fractions of a second after the Big Bang. But there is a link.

The abrupt change from ordinary to superfluid helium is an example of a phase transition. Assuming that the universe was once considerably hotter and denser than it is now, it's quite possible that analogous phase transitions occurred as the universe cooled.

By studying phase transitions in liquid helium and other materials in the laboratory, researchers hope to glean insights into how the universe evolved to its present state. Such experiments may also suggest why matter condensed into the distinctive hierarchy of clumps — from stars and galaxies to clusters of galaxies arranged into great walls and vast voids — visible in the sky today.

"Cosmologists have proposed a number of different models," says Bernard Yurke of AT&T Bell Laboratories in Murray Hill, N.J. "Experiment provides a check that the [theoretical] results one is coming up with really do make sense."

The central issue concerns what happens during a phase transition.

For example, when water freezes slowly, molecules initially moving at random settle into place to form a well-defined lattice, which grows in an orderly manner from a single starting point. If the process occurs quickly, however, ice crystals may start growing in several different locations at the same time.

Enlarging rapidly, these crystals eventually meet and merge. But because the crystals may have different orientations, defects occur at boundaries where molecules fail to align. In ice, such mismatches show up as milky filaments or frosty sheets suspended in the clear solid.

In 1976, Thomas W. B. Kibble of Imperial College in London suggested that a rapid phase transition just a tiny fraction of a second after the Big Bang may have created similar defects in the geometrical structure of spacetime. In this case, the phase transition involves a hypothetical force field known as the Higgs field, which gives spacetime a particular orientation.

According to this view, gravitational fields associated with the resulting stringlike cosmic defects set the pattern for the later emergence and aggregation of matter into stars and galaxies.

Noting the similarity between the mathematical model used by Kibble for the formation of cosmic strings and models used in condensed-matter physics to describe certain kinds of phase transitions, researchers have in recent years turned to laboratory experiments to test the credibility of Kibble's structure-forming mechanism.

One possibility involves tracking the behavior of certain kinds of liquid crystal materials — such as those found in calculator or digital watch displays.

These liquid crystals typically consist of large, rod-shaped molecules. Like molecules in an ordinary liquid, they normally have random orientations. Lowering the temperature or increasing the pressure induces these molecules to line up parallel to one another.

In 1991, Yurke, Neil Turok of Princeton University, and their coworkers demonstrated that a sudden increase in pressure forces a phase transition in which the liquid crystal shifts from a random to an ordered state. The change occurs so quickly that various types of defects form at the boundaries between patches of fluid having molecules aligned in different directions (SN: 6/1/91, p.344).

These experiments showed that a phase transition could generate linelike defects analogous to the cosmic strings of the Kibble mechanism.

"It was nice to be able to present a physical realization of these abstract ideas," Yurke notes.

To test the Kibble mechanism further, Mark J. Bowick and Eric A. Schiff of Syracuse (N.Y.) University and their coworkers measured the average number of string defects produced per ordered region, or domain, in a liquid crystal. The value they obtained, reported in the Feb. 18 SCIENCE, was in reasonable agreement with the predicted density of cosmic strings calculated using Kibble's theory.

At this stage, "you can really only say it's the right order of magnitude," Bowick remarks. "We're trying to do a better experiment now."

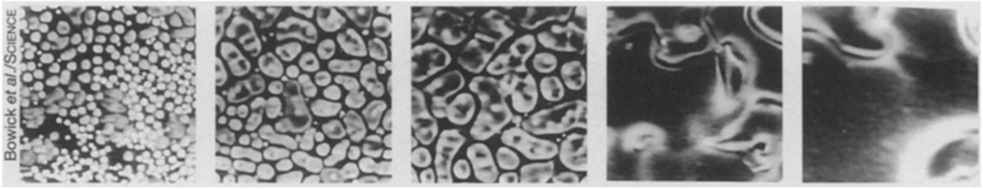
"We're also thinking of trying other kinds of liquid crystals," he adds. For example, with certain types, it's possible to get alternative defect geometries, including networks of strings.

Defects also occur when liquid helium undergoes a phase transition from its normal to its superfluid phase. In this case, the defects materialize as vortex lines — tiny, invisible whirlpools of fluid that penetrate the liquid helium.

Reporting in the March 24 NATURE, Peter V.E. McClintock of Lancaster University in England and his collaborators showed that a rapid phase transition in liquid helium does indeed create large numbers of such defects.

"These results support Kibble's contention that such defects were available in the early universe to seed galaxy formation," the researchers conclude.

Kibble's idea, however, is but one of a number of competing models — ranging from quantum fluctuations in a rapidly inflating universe to gravitational interactions involving dark matter — proposed for the origin of large-scale structure in the universe. The issue remains far from settled. ☐



Bowick et al./SCIENCE

In a matter of seconds, tiny bubbles form, grow, and coalesce into strings during a phase transition in a liquid crystal.