Seeding the Universe

By IVARS PETERSON

How did matter assemble itself into the giant filaments, clusters, bubbles and walls of galaxies that now fill the universe?

The cosmic book holds many mysteries. One of its great puzzles concerns how primeval matter, hurled uniformly in all directions by a violent explosion commonly called the Big Bang, could end up clumping into vast aggregations of stars and galaxies.

For a long time, theorists could speculate about the origin of galaxies with relative impunity. Their theories made few testable predictions, and observations that might restrict their flights of creativity were scarce.

But astronomers, painstakingly piecing together decades of observations, are providing an increasingly stringent standard against which to measure such theoretical notions. "What's happening is that a field that was really data poor is becoming data rich," says Margaret J. Geller of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., who has helped to map the distribution of galaxies across large parts of the sky.

The trouble is that no current theoretical model of the evolution of the universe seems to fit all of the observations without at least some inconsistencies. Cosmologists find they must labor to squeeze their pet theories into the steadily tightening straitjacket of observational data.

"Everything is moving along very rapidly," says James E. Gunn of Princeton (N.J.) University. "I suspect most of the ideas that we have now—and that some of us cherish—will before long end up in the wastebasket."

Such fundamental difficulties in setting the stage for galaxy formation are forcing cosmologists and astrophysicists to consider exotic, alternative models of how the universe evolved. In the past, many of these possibilities — cosmic strings, global textures, late-time phase transitions—would have appeared too strange for anyone to take seriously.

"The feeling that completely new thinking is required is so strong that people are trying out things they would have rejected before as too speculative," says William H. Press of the Center for Astrophysics.

Cosmologists must reconcile a number of separate, seemingly contradictory observations as they seek to explain the origins of the galaxies and the structure of the universe. First, galaxies appear to be receding from one another, with the more distant galaxies receding more rapidly. Second, the universe is filled with an astonishingly uniform glow of invisible radiation, known as the cosmic microwave background, which represents the heat left over from the creation of the universe (SN: 1/20/90, p.36).

Those observations, along with the observed abundances of the elements hydrogen, helium and lithium created in the initial explosion, support the simple picture of a symmetric, homogeneous, expanding universe. Indeed, cosmologists generally assume that a violent cosmic explosion marked the birth of the universe and the beginning of time some 10 billion to 20 billion years ago. In its earliest moments, such a universe would be extremely dense, unimaginably hot and virtually featureless.

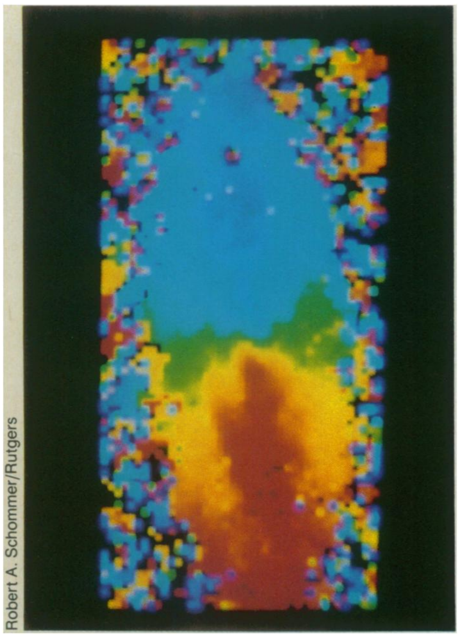
But this uniformity is difficult to reconcile with the obvious clumping of matter into galaxies, clusters of galaxies and even larger features extending across vast regions of the universe, such as "walls" and "bubbles" (SN: 11/25/89, p.340). At the same time, the detection of extremely distant quasars means that some galaxies must have already existed when the universe was less than a billion years old. Furthermore, large groups of galaxies seem to be streaming in particular directions—as if pulled by large mass concentrations — at significant fractions of the rate at which galaxies in general are spreading apart as the universe expands (SN: 1/27/90, p.60).

These observations pose considerable difficulties for those wedded to the idea of a uniform, explosive beginning. They force theorists to come up with a structure-forming mechanism that creates features as large as 5 percent the size of the whole universe from perturbations in the density of matter that a few hundred thousand years after the Big Bang could deviate from complete uniformity by only a few parts in 100,000.

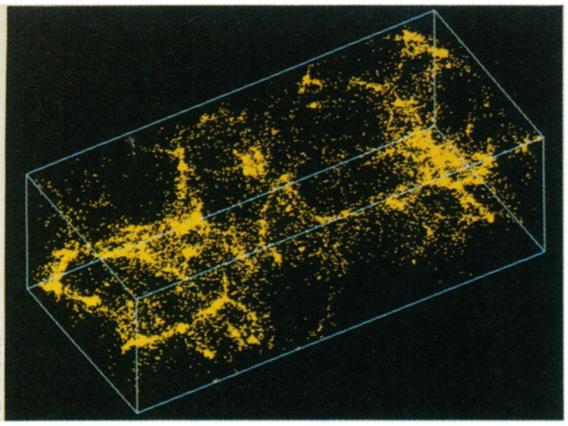
"That's really the crunch that has set theorists back to square one," Press says. "If it weren't for the microwave background, you could just say the structure is what it is, and you could work your way backward to find out what the initial perturbations were."

In its simplest form, the Big Bang scenario doesn't look like a good way to make galaxies. It allows too little time for the force of gravity by itself to gather ordinary matter—neutrons, protons and electrons — into the patterns of galaxies seen today. Yet the theory survives for want of a better idea.

"If there were an alternative model that explained the microwave background and the nucleosynthesis abundances observed, and produced galaxies, then people would start thinking about it," says



Detailed study of the motion of spiral galaxies helps astronomers determine how rapidly galaxies may be streaming in particular directions. In this picture of a rotating, spiral galaxy designated NGC4679, the different colors show the relative motion of different parts of the galaxies.



Park & Gott

Computer simulations demonstrate that the cold-dark-matter model of the universe can produce large, intricate structures representing vast aggregations of galaxies. This image, showing only 1 percent of the full simulation recently developed by Changbom Park and J. Richard Gott, reveals the fine structures visible in a block 780 million by 390 million by 260 million light-years.

Princeton's David N. Spergel. "But there's no good, viable alternative to the Big Bang."

The theorists' task lies in finding a physical mechanism for producing tiny fluctuations either in the geometry of space-time or in the density of primordial matter early in the history of the universe. Those fluctuations would have to be small enough not to unduly ruffle the microwave background yet large enough for gravity to amplify into the giant structures now apparent in the sky.

"It's pretty hard to generate density fluctuations if you start with a uniform universe," says Alexander Vilenkin of Tufts University in Medford, Mass. "Only in the 1980s did people start to come up with possible mechanisms."

Theorists approach the problem of generating fluctuations in two ways. Particle physicists start with mathematical expressions describing the fundamental forces in the universe. From these so-called field equations, which specify how one particle influences another, they then work out the properties of particles that may populate a given force field. Astrophysicists go in the opposite direction. They try to work out what kinds of elementary particles would be needed to create the patterns of galaxies seen in the sky.

It's a kind of guessing game, says David N. Schramm of the University of Chicago: "Let's guess some initial conditions. Can those initial conditions then give you the structure that's seen?"

The cold-dark-matter model of the universe is the most thoroughly investigated vehicle for generating minute density fluctuations as seeds for galaxy formation. This model postulates that starting about 10^{-35} second after the Big Bang, the universe suffered a cosmic burp, going through a brief period – only 10^{-33} second long – of rapid "inflation" when it expanded much faster than the normal Big Bang expansion observed today. Density perturbations, acting like waves washing through a thick particle soup, emerge naturally from random quantum fluctuations in the fields that drive inflation.

However, whereas astronomical observations of the motions of galaxies suggest that dark, hidden material is roughly 10 times more plentiful than luminous matter, the inflation scenario requires that the universe contain about 100 times more mass than telescopes can detect. Particle-physics theories suggest a variety of exotic candidates for this extra material – dubbed cold dark matter – but no one has yet proved that any of these postulated particles exist. Nonetheless, according to theory, such slow-moving, weakly interacting particles would make up most of the mass of the universe.

Although the identity of the elementary particles that might constitute cold dark matter remains a mystery, researchers can study generic cold-dark-matter models with characteristics largely independent of the particle physics involved. Massive computer simulations allow them to track how gravity would move matter around in a universe dominated by cold dark matter. And the results fit the observations surprisingly well.

Recently, two groups of Princeton researchers independently produced computer simulations demonstrating that gravity by itself could magnify tiny random fluctuations in the distribution of cold dark matter at the universe's very beginning to produce large-scale galactic structures (SN: 2/3/90, p.68). Another computer simulation, developed by Edmund Bertschinger and James M. Gelb of MIT, showed that such random fluctuations are also sufficient to start forming galaxies as early as a billion years after the Big Bang.

But these simulations still fall short of proving that the universe was dominated by cold dark matter as it evolved. For instance, they show too little detail to model the formation of individual galaxies, and the investigators must mark by hand the positions of galaxies within the large structures the computer model produces.

Deciding how to distribute the particles in the simulation representing ordinary, luminous matter against a background made up of particles representing cold dark matter is another vexing problem. In their computer version of a cold-dark-matter universe, Princeton's Changbom Park and J. Richard Gott, for example, adjust their model so that luminous galaxies are more clustered than the overall distribution of mass. They assume protogalaxies tend to concentrate in regions of higher-than-average density of cold dark matter, whereas low-density regions tend to harbor few protogalaxies.

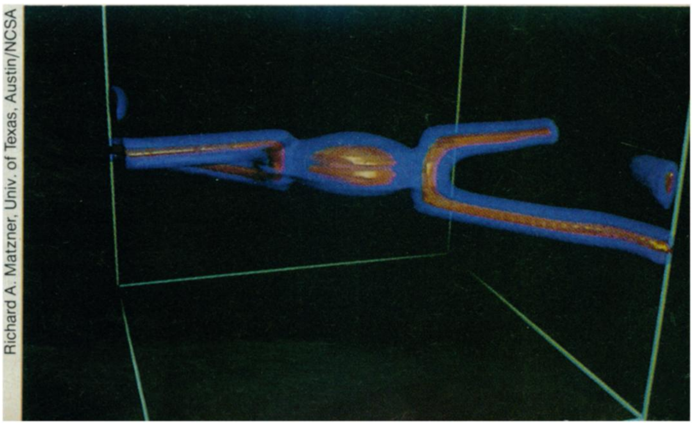
"There's no physical reason this should be true," Press says. "It could be a property of galaxy formation that in denser regions emission is more efficient. That's not an absurd hypothesis, but the only reason it was brought forward was to get the cold-dark-matter scenario to fit the observations."

Perhaps the most pressing challenge to cold-dark-matter models arises from observations of large-scale streaming. This cosmic drift, in which clusters of galaxies move as if they were being pulled by great concentrations of mass, produces galactic velocities that cold-dark-matter models have trouble matching. The models tend to produce much smaller streaming velocities.

At the same time, the theoretical underpinnings for the cold-dark-matter model are still not settled. Physicists remain uncomfortable with several aspects of the inflation scenario, which the model requires – especially with ideas on how to get inflation to stop so the simulated universe can resume its evolutionary course at a more sedate pace. Recent work suggests the possibility of an impor-

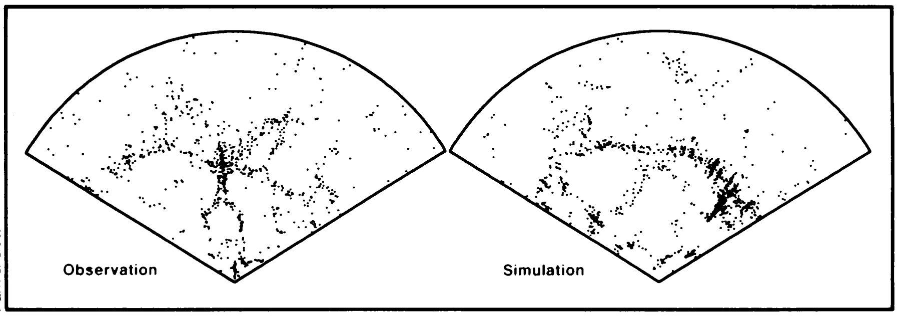
This frame from a movie simulating a cosmic-string collision shows the annihilation of the central parts of the strings, with the release of radiation. The strings break, then reconnect by switching partners to create new strings with straight segments joined by kinks.

Richard A. Matzner, Univ. of Texas, Austin/NCSA



tant interaction between inflation and gravity that modifies the force of gravity and helps bring the inflationary period to an end. That would change the value of the gravitational constant in the equation relating the gravitational attraction between two masses and the distance between them.

"It entails having the gravitational constant vary with time during inflation," says theorist Paul J. Steinhardt of the University of Pennsylvania in Philadelphia. "What we've learned over the last few months is that where you have fields that are coupled to gravity, you'll automatically get this kind of effect while you're caught in the inflationary phase."



Computer simulations based on a cold-dark-matter model of the universe can produce distributions of galaxies (right) reminiscent of the large structures observed by astronomers, such as the "Great Wall" (left).

Topological defects — patterns or cracks in the geometry of space-time — provide an alternative means of creating fluctuations that can act as seeds for galaxy formation. These bizarre features come out of particle-physics theories that try to provide a unified picture of the four fundamental forces in the universe: the gravitational, electromagnetic, weak and strong forces.

Many of the field theories that unify the fundamental forces suggest that during the universe's initial expansion and consequent cooling, a rapid series of phase transitions produced points, strands or walls of highly concentrated energy. Reminiscent of the frosty flaws that appear in a conventional phase transition, or change of state, when an ice cube freezes, this network of cosmic cracks — frozen into the fields that thread space-time — could supply a suitably disordered background for galaxy formation.

"Instead of using random fluctuations to make galaxies, we have some sort of intrinsic defect coming out of some fundamental physics," Schramm says. Different field theories, depending on their complexity, predict different kinds of phase transitions that lead to different kinds of space-time defects: domain walls, cosmic strings, monopoles, global textures. Any of these could act as the seeds for galaxy formation.

One-dimensional faults, known as cosmic strings, at one time looked very promising as a vehicle for structure formation. Consisting of extremely thin tubes of space-time, these high-density, high-energy strings would form a tangled network threading the entire universe. Cosmic strings have no ends and would form either as closed loops or as infinitely long strands.

The original idea was that closed loops, roughly the size of galaxies, could act as seeds whose high density would gravitationally attract matter and lead to the formation of galaxies and clusters of galaxies. But recent computer simulations of the behavior of loops show that cosmic strings, if they exist, evolve in much more complicated ways than theorists had initially thought.

"The evolution of this tangle of strings is rich in physical processes," Vilenkin comments in the Feb. 15 NATURE. Vilenkin was among the first to propose that cosmic strings might explain clumping of matter into galaxies.

Tension in curved strings makes them wiggle violently, and they often cross one another, Vilenkin says. Intersecting strings break at the crossing point and reconnect by exchanging partners. These strings develop sharp kinks at the points of reconnection. Moreover, long, twisted strings can cross themselves many times, shedding their coils in the form of closed loops, which fragment further. The smallest loops gradually lose their energy, producing gravitational waves as they shrink and disappear.

But recent computer simulations show that the resulting loops would be too small to seed galaxy formation. "The old picture, where galaxies formed around loops, is basically dead," says Princeton's David P. Bennett. "But it doesn't mean that strings are no good for galaxy formation." Bennett and François R. Bouchet of the Institut d'Astrophysique de Paris summarize the results of their latest cosmic-string simulations in the Dec. 25, 1989 PHYSICAL REVIEW LETTERS.

Theorists are now focusing on the wakes created when a long string whips through an initially uniform distribution of matter. Such wakes could result in sheet-like distributions of matter — similar to the walls of galaxies observed.

"If strings are really responsible for structure formation, the new simulations show it will be wakes rather than loops," Vilenkin says. "But because the evolution of strings is pretty complicated, the only way to really assess this scenario is to combine computer simulations of evolving strings with simulations of how matter clusters due to gravity." That's a formidable computational problem.

"We haven't done any realistic calculations yet, but I'm fairly optimistic that we might be able to come up with a pretty good scenario," Bennett says. "Part of the problem is that the calculations for long strings are considerably more difficult than the ones with loops."

To complicate the picture further, theorists can also try to work out what happens when cosmic strings interact with cold dark matter or with massive neutrinos (known as hot dark matter). And what if the universe had a primordial magnetic field? Then so-called "superconducting" cosmic strings could have carried immense electric currents as they thrashed around. Such strings would, in effect, push matter rather than attract it. However, measurements from the Cosmic Background Explorer spacecraft show no excesses in the cosmic microwave background that could be attributed to radiation generated by superconducting strings.

In the Dec. 11, 1989 PHYSICAL REVIEW LETTERS, Princeton's Neil Turok proposes an alternative type of topological defect for supplying high-density seeds for galaxies: global texture. Such defects arise from unified field theories somewhat more complicated than those producing cosmic strings.

The fields thought to thread the cosmic vacuum are known as Higgs fields. It's possible to picture such a field as a set of arrows at each point in space. Each arrow has a direction that changes continuously from point to point. Together, the arrows form swirling patterns.

As a universe with texture evolves, the swirls, or twists, collapse into small regions of high energy density, which Turok calls knots. When the energy density gets high enough to "melt" the Higgs field itself, the knot unravels, and the knot's energy radiates away in a spherical blast wave.

Turok suggests that objects ranging in size from galaxies to giant superclusters of galaxies might condense either about the knots or at intersections of blast waves from the annihilation of neighboring knots. Whereas cosmic strings lead to the accumulation of matter, global texture readily generates voids, carving out vast regions in which few galaxies would form. That produces a universe with a bubbly structure, apparently consistent with what astronomers observe.

"We're at the very early stages, but it looks promising," Spergel says.

Whereas cosmic-string and global-texture scenarios arise from phase transitions that produce topological defects in the first second of the universe's existence, an alternative model suggests that a much later phase transition could have been responsible for the fluctuations that led to galaxy formation (SN: 4/29/89, p.262).

Schramm and his colleagues contend that such a phase transition could have occurred a million or so years after the Big Bang. One mechanism for this type of transition rests on the possibility that neutrinos – subatomic particles thought to have no mass at all – may actually have a tiny mass, which would manifest itself at such a late time. That transition could produce topological defects known as domain walls.

However, recent computer simulations show that the domain-wall scenario doesn't work well because it predicts larger distortions in the microwave background than those actually observed. But there are other possibilities. For example, domain walls may slough off fragments (balls of wall), which could end up as seeds for making galaxies. And present particle-physics theories leave room for a variety of exotic particles that could participate in a late-time phase transition.

"Some of these options look quite promising," Schramm says.

Press, for instance, is thinking about particles he calls "soft" bosons. "You could have a late-time phase transition that essentially fills the universe up with particles," Press says. Each particle would be about the size of a galaxy but would have a tiny mass so that large numbers of the particles would coexist and overlap.

"Such particles would act like cold dark matter," Press says. "But their existence would solve the mystery of why cold dark matter doesn't end up falling into galaxies. They're just too big." Press, Spergel and Barbara S. Ryden of the Center for Astrophysics describe their first encounter with soft bosons in the March 5 Physical Review Letters.

The trouble with such scenarios is that they require very special conditions. "A lot of strange things would have to happen just to make that late phase transition," Steinhardt says. "You have to explain why there are phase transitions at low energies that you don't observe in the laboratory."

Schramm adds, "The idea of doing things by a late transition seems to be sparking a lot of attention. But it needs to be tested by more observations and calculations. Whether it describes the universe quantitatively rather than just qualitatively remains to be seen."

The answer to the puzzle of the origin of galaxies is written in the giant filaments, clusters, voids and walls visible in the skies today. But scientists don't know yet whether they have the key needed to unlock the secret. "There is no compelling theory of structure formation," Vilenkin says. "All the theories that we are playing with now may turn out to be wrong."

The standard cold-dark-matter model remains the prime candidate, partly because it has been the easiest to study in detail. "It's a very simple theory that makes strong and concrete predictions," Gunn says. In contrast, "people are still arguing about the consequences of the other, wilder things like strings."

"Once a theory becomes entrenched, it takes a lot of evidence to ditch it," says Robert J. Scherrer of Ohio State University in Columbus. "Cold dark matter will stay the standard model until there's overwhelming evidence against it. We haven't reached the overwhelming point yet, but problems are piling up." Scherrer has worked on both cosmic-string and hot-dark-matter models of galaxy formation.

"It's getting tough to be a theorist," Spergel says. "The observers are doing their job, and the theorists have to do their job and develop these ideas so they can be compared directly with the observations to see how they stand up."

That's not easy to do. In both the cosmic-string and cold-dark-matter models, researchers have already found that larger computer simulations incorporating more details often produce results quite different from those coming out of smaller, less detailed simulations.

"That opens a Pandora's box of things being more complicated and depending in more subtle ways on little details you might not pin down in a short simulation," says Andreas Albrecht of Fermilab in Batavia, Ill. "How then do you extrapolate from a short numerical simulation to the time span of the age of the universe?" Albrecht has plunged into computing the details of cosmic-string models to see if they can still be saved. Nonetheless, he concedes, "my hunch is that something new is necessary."

"We would all feel much better if you could do one calculation that did everything," Gunn says. "But it's going to be a long time before we can do that."

At the same time, theorists shouldn't forget the uncertainties in astronomical data. For example, determinations of the velocities of galaxies depend on accurate distance measurements, and astronomers are still debating how to establish distances beyond our own galaxy.

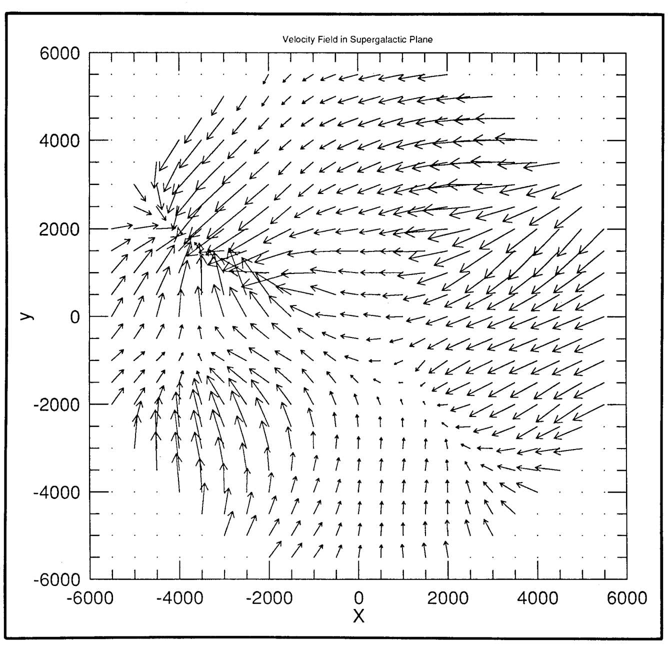
"Part of the problem is that if you take all the observations, there's a reasonable chance that maybe one of them isn't quite right," Bennett says. "But it's hard to know for sure which one. Most of them are pretty compelling on their own."

In a 1988 review article in Nature, P.J.E. Peebles of Princeton and Joseph Silk of the University of California, Berkeley, asked the question: "Will our feeble minds ever comprehend the evolution of the Universe?"

They concluded on a tentative note: "For now, we can enjoy the spectacle as theoretical and observational discoveries continue to press and stimulate cosmological theories."

Those words ring just as true today.

"If you're young, it's a particularly exciting time," Scherrer says. "It's no fun to be in a field where the theory has been settled and all there is to do is to cross the t's and dot the i's. It's much more fun to be in a field where everything collapses suddenly." □



Bertschinger, Dekel, Faber

On this map of a slice of the universe in the neighborhood of the Milky Way, which sits at the map's center, arrows show how rapidly galaxies are moving in particular directions. In general, these galaxies, including the Milky Way, seem to be moving toward an apparent concentration of mass now known as the "Great Attractor" (upper left).