A Computer-Generated Cosmic Portfolio

By training computers to simulate the histories of many plausible universes, cosmologists hope to better understand the particularly puzzling one we inhabit.

By PENNY D. SACKETT

In 1965, two Bell Laboratory scientists named Arno Penzias and Robert Wilson discovered cosmic static in their radio receiver. Modern cosmology, the study of the origin, evolution and structure of the universe, was born. The realization that this cosmic microwave hiss was a signal from the universe's extremely hot youth pounded the final nail into the coffin of some long-standing cosmological theories. Left as the strong front-runner was the "big bang" model — wherein the cosmos expanded from its birth in a gigantic explosion of space and energy.

Many of the later-discovered inadequacies of the original big bang model have been successfully addressed by new and shinier models, offspring of the recent marriage of cosmology and particle physics. Yet, some deceivingly simple questions remain unanswered: Why is the matter in the universe distributed in its present pattern? Is the universe composed of primarily luminous matter, or are some dark cosmic constituents eluding our vision?

Researchers first in the USSR and now also in the United States are hoping to solve these old astrophysical riddles by using information from particle physics as input for huge computer codes which simulate the evolution of several possible universes. These cosmological biographies are contrasted with observational knowledge of our own universe in an attempt to find a match.

All of this is, of course, quite a grand ambition. How could one possibly hope to trace the history of an entire universe? The answer lies in simplifying the model in question until it is stripped of all but a bare minimum of pertinent characteristics. Even so, to trace once through a particular cosmological history can require three continuous hours of computer time and computer codes so large that they strain presently available computer storage.

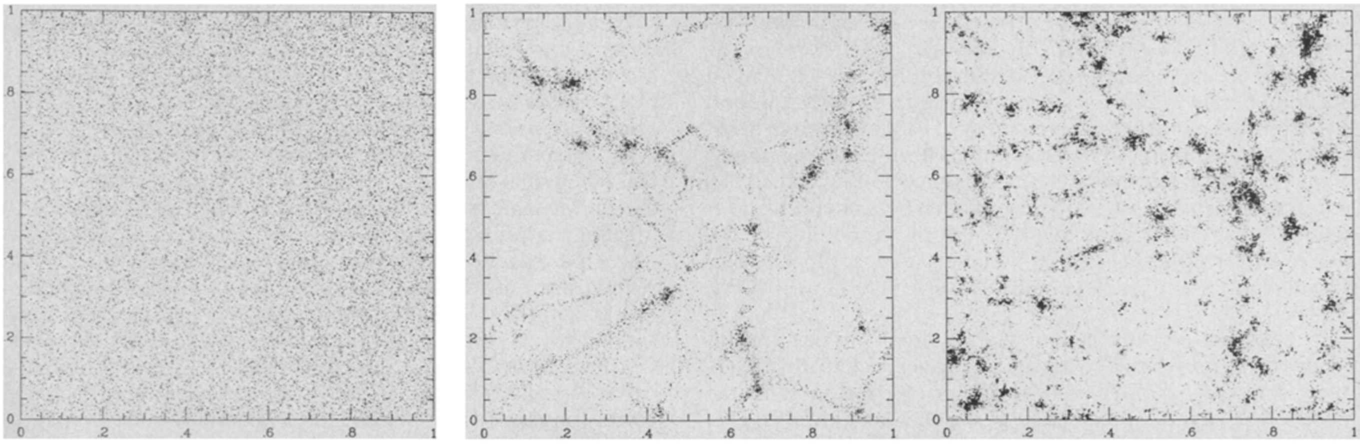
A simulation is initiated when the researcher tells the computer how matter interacts and describes initial particle speeds and positions believed to be representative of those at early times. Evolving the matter through the past to the present, the computer then does the rest, giving the researcher a "snapshot" of the speeds and positions of matter at any time in the life of this particular model universe.

Since computer space and time are limited, nearly all simulations done to date have followed the history of only a single kind of particle. The outcome of these simulations depends primarily on the "density perturbation spectrum" of the chosen particle, that is, on precisely how the matter is believed to be distributed when the universe is young — information donated by particle physics.

A good first guess might be to assume that at early times, hydrogen, the most abundant elemental constituent of the universe, was distributed randomly throughout the cosmos. Although the hydrogen we see now certainly is *not* randomly distributed (it's gathered into lumps called galaxies and oceans and people), perhaps over time mutual gravitational attractions could clump initially random matter into an uneven distribution.

Computer simulations done in the late 1970s to test this hypothesis were encouraging. Beginning with an initially random pattern of particles distributed throughout the early universe, and assuming that the matter interacted only gravitationally, computer codes evolved the particles through time. Snapshots representing how such a model universe might look at present times showed very clumpy distributions of matter reminiscent of the blotchy character of our universe.

But our universe is lumpy in a *particular* way. The relatively small lumps of ignited hydrogen that we call stars are separated by vast wastelands nearly devoid of matter. Galaxies, which are aggregates of billions of stars, are further clumped by the hundreds and thousands into loose neigh-



White, Frenk, Davis

Initial snapshots of a neutrino-dominated and initially random hydrogen-dominated universe would look much the same to the untrained eye (left), but as the computer evolves the models through time, the differences become striking. The distribution of luminous matter in the neutrino model (middle) shows long, thin filaments and large, empty voids not seen in the hydrogen model (right). Shown here are cross-sections of three-dimensional models.

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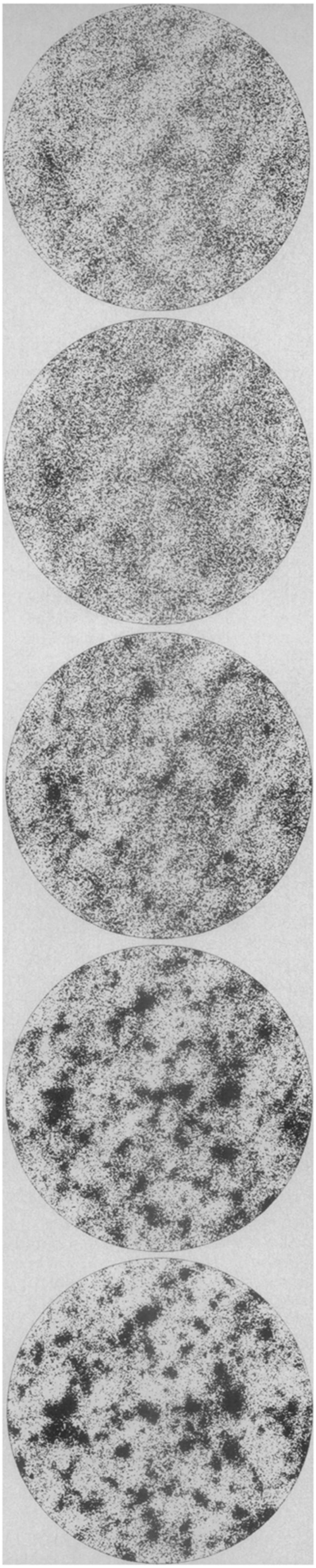
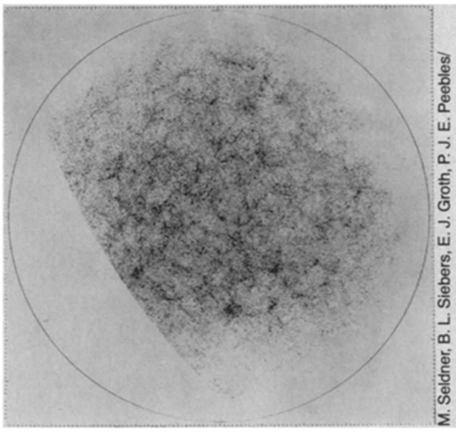


S. Matsik/Univ. of Pittsburgh

The panorama of clustering is biased from an earth-based view. A quite distant, but bright, galaxy may appear to be close neighbors with a nearer, dimmer galaxy. Successive snapshots of a three-dimensional neutrino computer model are shown here as they would appear to a random observer looking at the night sky (left, top to bottom). Comparison with an actual map of the galaxies in the northern galactic hemisphere (right) will indicate that the neutrino model may be too lumpy to agree with astronomical observations.



M. Seldner, B. L. Siebers, E. J. Groth, P. J. E. Peebles/ Astronom. J., 82, 249, 1977

borhoods called clusters. Finally, the galaxy clusters themselves are grouped into enormous spaghetti-like strings known as superclusters — a single one may stretch one one-hundredth of the way across the entire universe with comparatively empty voids in between.

To measure the specifics of clustered matter distributions, astrophysicists use the "auto-correlation function." Simply put, starting with any particular galaxy, the auto-correlation function measures the odds of finding another galaxy at a given distance away. This probability will vary, in general, as the distance is changed.

To test the success of the simulations that relied on initially random organizations of matter, the auto-correlations of the computer-generated snapshots were compared to those of real astronomical observations. Now the trouble began. The two auto-correlations did not match, especially at very large distances. Furthermore, the filamentary structure of superclusters and the huge voids seen in between had not been reproduced in the computer simulations.

"Although the people that did the simulations argued quite strongly that what the observers were seeing was just an ordinary statistical effect enhanced by their imaginations,...I think a lot of people were never convinced by those arguments. And so people began looking for a different kind of initial condition which would produce a universe in which you could, in fact, find filaments and holes." So relates Simon White, astrophysicist at the University of California at Berkeley, who is working with colleagues Marc Davis and Carlos S. Frenk on many ongoing computer simulations of just that type.

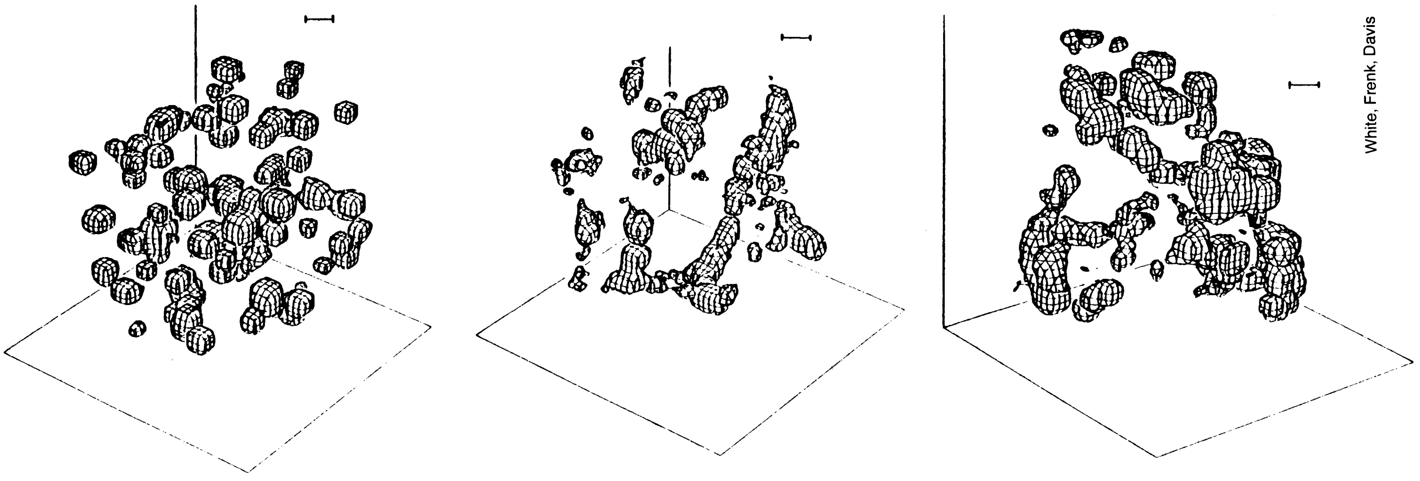
At first, one might suppose that by simply varying the initial lumpiness of the matter in just the right way, one could achieve a model universe that would then evolve to give the proper auto-correlation function observed today. But not only is this just plain cheating, the early distribution of hydrogen-like matter is fairly firmly determined by theory. It is not free to be varied at the whim of a cosmologist.

According to current cosmological theories, as positively charged protons began to latch onto negative electrons to form hydrogen in the cooling half-million-year-old universe, photons of light were freed from their bondage to this matter. Free from scattering, this "decoupled" light could then travel basically unheeded throughout the cosmos, cooling with it: a relic of the big bang and a sign of what the universe had once been like. This ancient light, cooled to microwave frequencies, was the source of the annoying noise in Penzias and Wilson's horn-shaped antenna. Subsequent measurements of this background radiation have shown that after corrections are made for the earth's motion through the cosmos, the earth receives the same amount of this microwave static, at the same temperature, from all directions in space. This uniformity has implications for the early cosmic distribution of hydrogen.

Since the photons were linked intimately to subatomic matter just before the "decoupling" time, the smoothness seen now in the cosmic microwave radiation indicates that the pairing protons and electrons were also distributed evenly at the decoupling time. The computer simulations have shown that, even with the help of gravity, the predicted smooth initial distributions of light and hydrogen cannot account for the observed hierarchial clumping of matter in the present universe.

Perhaps the researchers had over-simplified their computer models, overlooking some subtle but important effects. Perhaps quantum fluctuations at the time of the universe's birth were more important than previously thought (SN: 9/3/83, p. 152). Or perhaps another kind of matter is an important actor in the life of the universe.

Cosmologists weren't the only ones asking this last question. Clustered galaxies clocked at high speeds had been puzzling astrophysicists for years. The estimated mass of these galaxies was too small to hold them into a gravitationally bound cluster at such high speeds. But the mass estimates were based on the amount of luminous matter in the galaxies—perhaps some dark, unseen mass is providing the extra-gravitational tug.


White, Frenk, Davis

A three-dimensional view of a computer-generated section of: an initially random hydrogen-dominated universe (left); a massive neutrino universe (middle); and an actual sky survey (right).

Various candidates for this dark matter have been proposed, including: cosmic dust, cold planet-sized rocks, black holes and a variety of particle species from the heavily populated zoos of particle physics. If the dark matter exists in large amounts, cosmologists realized that they needed to know more about it so that the computer codes could be modified.

The amount of luminous matter that can be seen by astronomers suggests that the universe is diffuse enough to continue expanding forever. If the cosmic density is greater than "closure" density, however, the universe is so dense that its own gravitational attraction would eventually triumph over expansion and the cosmos would collapse back onto itself sometime in the distant future. Dark matter in the amount needed to explain galactic clusters would increase the density of the universe enough to push it to at least two-tenths of that needed for closure.

Some cosmologists feel that this effect rules out some of the proposed choices for the unseen matter on the basis of the existing theory of cosmic nucleosynthesis. At the time of nucleosynthesis in the universe's infancy, high temperatures and densities worked as a fusion catalyst for the heavy so-called baryonic matter found in nuclei. Small amounts of helium and deuterium were formed from hydrogen.

Adrian Melott is a cosmologist at the University of Chicago who was prompted to do computer simulations of the universe's history while studying the dark-matter dilemma. He explains, "The nucleosynthesis arguments say that if the density of the universe were greater than about 0.2 [of closure density] in just baryonic matter (protons, neutrons, atomic nuclei), there would be much more helium produced than is observed and far too little deuterium. This says that the baryon density of the universe cannot be greater than about 0.2 of closure, so there's a contradiction here with dark-matter calculations. In order to resolve that contradiction, some of the matter that's producing the gravity needs to be non-baryonic."

And so it seemed that the dark matter nominees must not only be found in copious amounts in galactic clusters, but if the arguments concerning nucleosynthesis were correct, they must also be composed of leptons — a lightweight class of weakly interacting particles.

This latter criterion eliminated cosmic dust, rocks and black holes from the competition and left particle physicists searching their theoretical zoos for leptons that would fill the cosmological bill.

The most obvious candidate was the well-known and abundant (about 100 to the thimble-full) neutrino. Because they decoupled from the rest of cosmic matter quite early on — about 100 seconds after the cosmic birth — neutrinos may have had lumpier distributions than hydrogen at the photon decoupling epoch, which is the usual starting point for computer simulations. Although this evidence was encouraging, the neutrinos were missing one key ingredient — mass!

Then, in 1980, a controversial Soviet experiment claimed to show that neutrinos have a minuscule, but definitely non-zero, rest mass (SN: 10/11/80, p. 228). The proposed neutrino mass would provide about the right amount of the "missing mass" in galactic clusters. Furthermore, if the Soviets were right, the neutrinos would also add enough mass to the cosmic density that the universe's ultimate fate could be a monstrous collapse sometimes known as the "big crunch."

Particle physicists and cosmologists alike immediately began studying the implications of non-zero neutrino rest mass. Computer simulations were developed by the Berkeley group and independently by Melott and Joan Centrella (then at the Universities of Pittsburgh and Illinois-Urbana respectively) to test how a universe dominated by the light but ubiquitous neutrinos would evolve through time. Theories from particle physics provided the necessary input concerning the likely initial neutrino distributions.

Progressive snapshots of these neutrino-dominated universes were striking. Over time, gravitational interactions did cause clumping in these models, just as in the hydrogen models—but the end results looked quite different.

In the early neutrino pictures, the matter seemed to form large, flat pancake structures. As the computer evolved the model, matter could be seen collecting

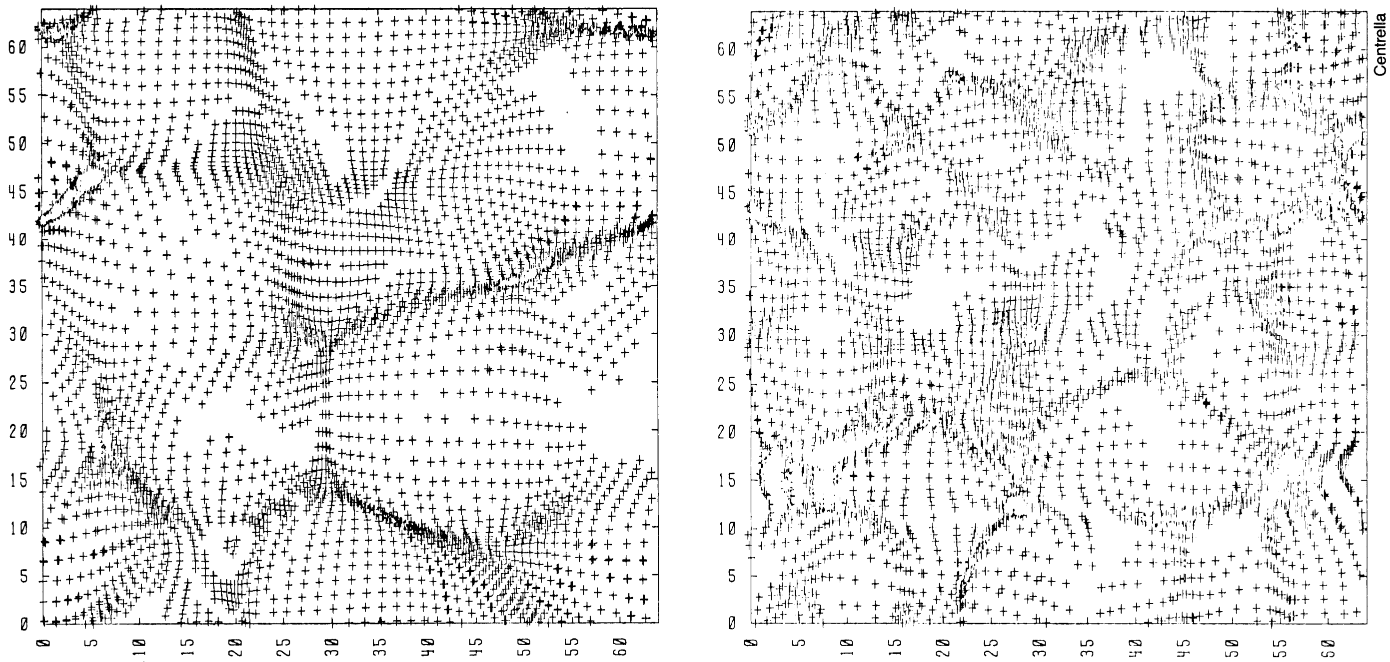
Teaching

Computers have long been aiding scientists in solving problems that engage human curiosity, but whose solutions involve the drudgery of repeated, complex and time-consuming calculations. Cosmologists interested in contrasting the various histories of the universe that are implied by differing theoretical models must mentally trace the evolution of great clouds of matter through cosmic time. The task is formidable. And so, some cosmologists have turned to the computer as a scientific tool, using it simply as a more sophisticated and somewhat larger version of the pocket calculator.

The results have been tantalizing if inconclusive (see accompanying story). They would also have been impossible to obtain without utilizing the computer.

In any use of a computer, the framework is the program, that is, the set of instructions that the computer will carry out. To begin executing the program, the computer will need some initial information called input. The results, or output, of the program execution are usually numerical in nature, but in the case of these specific cosmological programs, can be converted into pictures that correspond to a snapshot of the model universe at a particular instant of cosmic time.

These programs require as input the initial speeds of the particles that will participate in the gravitational interac-



Centrella

Two-dimensional slices of a three-dimensional cosmic neutrino model show in cross-section large, flat pancakes separated by empty voids (left). In contrast, preliminary results for models dominated by the theoretical gravitino, photino or axion particles reveal more small clumps in addition to the larger structures (right).

Computers to Do Cosmology

tions throughout the computer-simulated cosmic evolution. It is the exact distribution of these speeds that will determine whether small clumps of matter are dispersed, or will survive long enough to build galaxies. Particle physics theory provides information about the spectrum of these speeds by considering the nature and quantity of particles in the very early times of the hot, dense cosmic birth.

The program then uses this input to pick up the story of the evolving cosmic model in progress, about a half a million years after the big bang. Since it would tax the abilities of even the largest and fastest computers to trace the paths of all the particles, large numbers of the particles are imagined to form loose clouds, and the computer calculates and records the positions and speeds of the clouds as the simulation proceeds.

The programs used by different research groups vary in their details, but resemble closely the one currently used by astrophysicist Joan Centrella of the University of Texas at Austin, and her colleagues.

They begin by considering the model universe to be a large box, sectioned by an imaginary grid into smaller boxes, or cells. To trace the paths of the clouds through the grid, the gravitational force on each cloud due to its neighbors must be calculated. From this force, the change in a cloud's velocity may be determined, and thus a new velocity is obtained from the older, initial input.

Centrella describes the process. "What you first do is to say, 'Let's calculate the density of the matter on this grid.' To do this you have to go in and look at each cell on the grid, find out what fractions of each cloud is lying within that cell, and add up all the mass. That will give you a density array and this tells you the gravitational potential on your grid. Now you go back, and you look at a cloud, you find its position within this density array and you calculate the gravitational force on it, depending on where it lies. And then you push it."

All of the work described by Centrella, is, of course, done by the computer. The clouds will tend to move across the grid from cell to cell in the course of the simulation, with the computer recording their positions and speeds all the while. The updated velocities will serve as new initial velocities for the next pass.

As the output is processed into "snapshots" to be placed in the historical album of the particular model under study, cosmologists scan the pictures for familiar structures. They ask whether the simulated pictures look anything like actual maps of the universe in which we live. The answer is sometimes encouraging but usually disappointing, and the cosmologist is sent back to the drawing board to find a modified model that can provide new and improved input to the program.

Evolving cosmic histories in this way is tedious, repetitious and time-consuming. Though computers are quite capable of this sort of work, they cannot insert the necessary scientific care. This must be supplied by the cosmologist.

Centrella and her co-workers have done simulations with nearly a million clouds; it is important to have a large enough number of clouds so that they overlap inside the box. If they do not, lumpy, beady structures will form that represent not an interesting feature of the cosmic model but merely a defect in the choice of program and input.

It is also important, for similar reasons, that the calculation of the density array be done as accurately as possible and fine-tuned to different positions even within the same cell. The size of the overall box, meanwhile, must be large enough to easily contain the largest structure that will form in the simulation process.

All of these technical details require that the computer work longer and harder. The speed and storage capabilities of present-day computers are already being strained to their limit. Cosmologists now await, along with a host of other scientists, the advent of bigger, better and faster computers. If the improved machines arrive, the cosmologists will not be found wanting for ideas.

—P. D. Sackett

along the string-like intersections of these pancakes and then further clumping at the intersections of these strings. Large voids separated the string-like structures from one another. The filaments seen in the computer simulations had about the same length as those reported by the astronomical observers.

Although only neutrinos were studied in these simulations, researchers believed that the ordinary "hydrodynamic" baryonic matter (found in stars and human beings) would probably tag along with the neutrinos, reacting to their strong gravitational tug. When the weakly interacting neutrino clouds collided and passed through one another with little effect, the hydrodynamic matter, it was thought, would get trapped in the collision zones, shock and warm to high temperatures. Perhaps superclusters, clusters and galaxies could fragment from this ordinary matter squashed in the neutrino-formed pancakes.

But the proof of the pudding still remained in the auto-correlation test. A snapshot was found in the neutrino album that had the proper auto-correlation function. Unfortunately, says White, the snapshot showed a universe too young to correspond to the present time. In it, matter would be just starting to clump; galaxies just beginning to form.

He explains, "We had to go back to such an early time in the simulation that we were saying that galaxies formed yesterday — which is not consistent with observation."

Possible loopholes exist, since the computer simulations are known to have shortcomings. The "shocking" interactions of hydrodynamic matter may play an important role in galaxy formation. Even though the assumption had been made that the neutrino density dominated the universe, perhaps information about the heavier but more sparse baryonic matter should have been incorporated. This model is much more complicated than the pure neutrino models, however, and therefore requires more computer time and storage.

Astrophysicists Jim Wilson of Lawrence Livermore National Laboratory (LLNL) in California, Centrella, currently at the University of Texas at Austin, and Melott are working together to produce these more detailed simulations.

Meanwhile, both they, Soviet researchers in Moscow and Estonia, and Davis, Frenk and White have moved on, undaunted, to consider still more controversial particles as the mysterious dark matter. The latest models rely, not on existing particles that may or may not have mass, but on theoretical massive particles that may or may not exist: axions, gravitinos and photinos.

The results are preliminary, but encouraging. The relatively slow speeds of these particles at early times in cosmic history allow them to clump more easily, even in small groups. The result is that in the axion, gravitino and photino models, small cosmic structures seem to evolve along with the larger ones, and at more appropriate times. The snapshots corresponding to recent cosmological history bear more resemblance to astronomical observations than did the neutrino snapshots. But White warns that more work needs to be done on these models before firm conclusions can be drawn. The appearance of small clumped regions of matter in these models requires that further sample histories be done that are capable of distinguishing fine structures.

Present work by these two U.S. teams and by astrophysicists in the USSR will concentrate on incorporating baryonic matter into their codes, testing new types of dark-matter candidates and improving the spatial resolution of their computer models.

If they succeed in demonstrating that the dominant actor in galaxy formation and the overwhelming constituent of the cosmos could be a heretofore obscure lepton, it would be more ego shattering than Copernicus' heliocentric solar system. Not only is our position in the heavens completely undistinguished, but our very baryonic make-up might then be only so much inconsequential dust riding about on great gusts of leptonic gravity. □