Cosmos in a Computer

Capturing the full sweep of observable space and time, the largest cosmological simulation to date shows how gravity built the giant structures that fill the visible universe

A team of astrophysicists and computer scientists has journeyed to the far reaches of space and time by capturing the entire observable universe in a computer. They have created the first simulation of how gravity could have gathered ripples left by the big bang into colossal structures—walls, clumps, and filaments of galaxies—filling all of space. The result is a coarse-grained look at cosmic history within a cube 10 billion light-years on a side, a volume so big that if Earth sat in one corner, the far corner would hold some of the most distant galaxies and quasars ever seen.

"This simulation marks a turning point in numerical cosmology," says Michael Norman, a computational astrophysicist at the University of Illinois, Urbana-Champaign, who is not a member of the multinational simulation team, called the Virgo Consortium. Many times larger than any earlier effort, the whole-universe computation taxed the ingenuity of programmers and the number-crunching prowess of a 512-processor Cray supercomputer at the Max Planck Society's computing center in Garching, Germany. Other cosmologists have had little time to absorb the results, which were discussed late last week at a cosmology meeting in Paris by Jörg Colberg of the Max Planck Institute for Astrophysics (MPA) in Garching and which will be the subject of a talk by August Evrard of the University of Michigan at next week's American Astronomical Society meeting in San Diego. But they say they expect this model universe to be a powerful tool for interpreting data from large surveys of the real sky.

Norman, for instance, notes that even the biggest survey of the real sky, the 5-year Sloan Digital Sky Survey (*Science*, 29 May, p. 1337), will map just 100th of the visible universe, so astronomers can't be sure they're getting a true sample of galaxy clusters and voids. But because the simulation covers "essentially the entire visible universe," he says, even rare structures should crop up often enough to settle questions about how typical they are. Adds Martin Rees, a cosmologist at Cambridge University in the United Kingdom, "It is splendid that the modeling and simulations have attained this level of sophistication just at the time when we are starting to get a flood of high-quality data."

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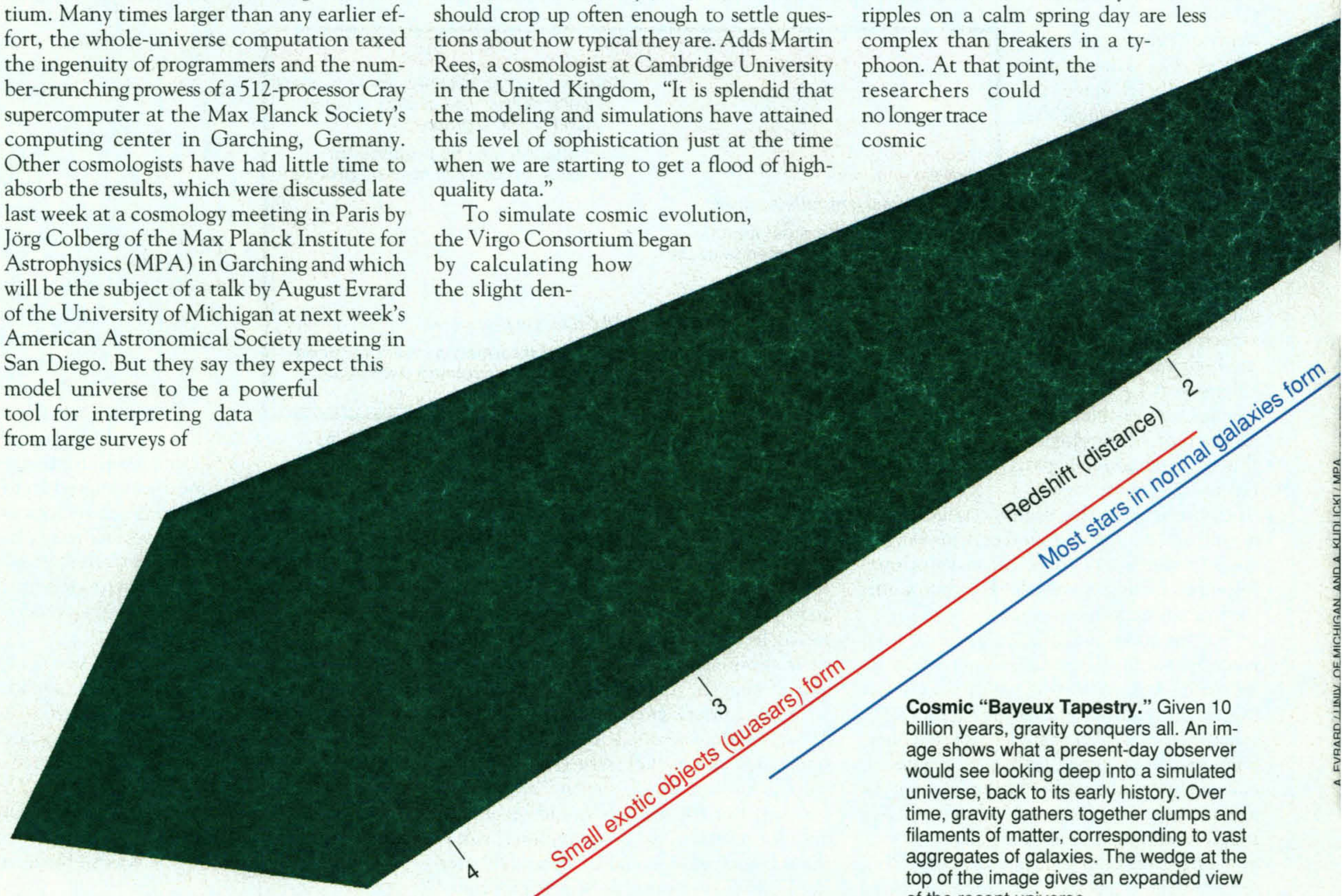
—Michael Norman

To simulate cosmic evolution, the Virgo Consortium began by calculating how the slight density variations rippling through the matter of the very early cosmos might have grown. Those ripples are thought to have originated as "quantum fluctuations"—in essence, waves of uncertainty in particle positions—during the first instants of the big bang, when the entire observable universe was no larger than a grapefruit. Relatively simple calculations predict how radiation in the hot young cosmos would have smoothed out some of these perturbations while allowing others to intensify.

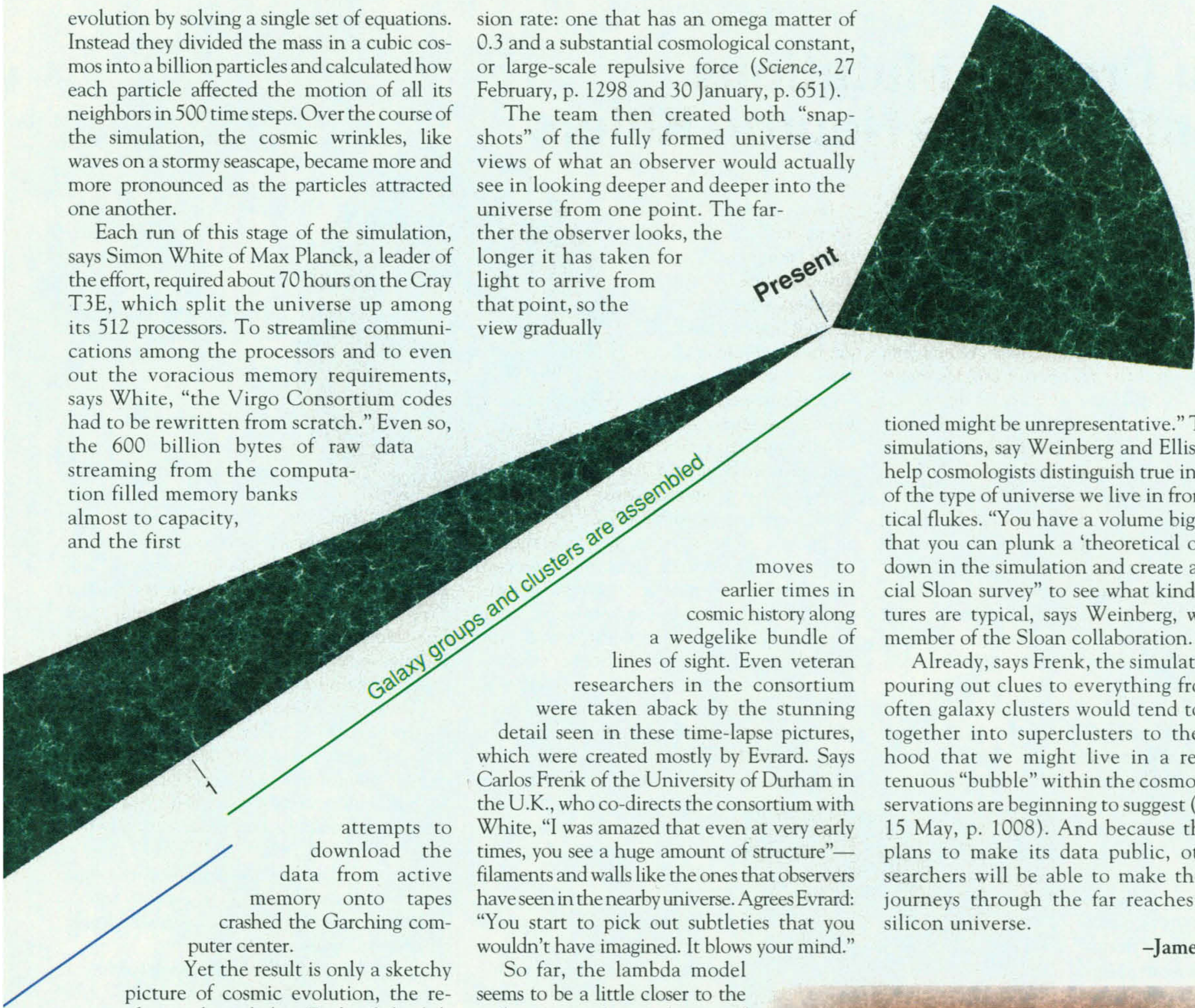
As the universe expanded and cooled, gravity took over. And after about a billion years, when the cosmos was about 10% of its present age, concentrations of mass equaling tens of Milky Ways began to "go nonlinear," becoming too closely bunched for simple mathematics to handle—just as seaside ripples on a calm spring day are less complex than breakers in a typhoon. At that point, the researchers could no longer trace cosmic



Cosmic "Bayeux Tapestry." Given 10 billion years, gravity conquers all. An image shows what a present-day observer would see looking deep into a simulated universe, back to its early history. Over time, gravity gathers together clumps and filaments of matter, corresponding to vast aggregates of galaxies. The wedge at the top of the image gives an expanded view of the recent universe.

A. EVRARD / UNIV. OF MICHIGAN, AND A. KUDLICKI / MPA evolution by solving a single set of equations. Instead they divided the mass in a cubic cosmos into a billion particles and calculated how each particle affected the motion of all its neighbors in 500 time steps. Over the course of the simulation, the cosmic wrinkles, like waves on a stormy seascape, became more and more pronounced as the particles attracted one another.

Each run of this stage of the simulation, says Simon White of Max Planck, a leader of the effort, required about 70 hours on the Cray T3E, which split the universe up among its 512 processors. To streamline communications among the processors and to even out the voracious memory requirements, says White, "the Virgo Consortium codes had to be rewritten from scratch." Even so, the 600 billion bytes of raw data streaming from the computation filled memory banks almost to capacity, and the first attempts to download the data from active memory onto tapes crashed the Garching computer center.



Yet the result is only a sketchy picture of cosmic evolution, the researchers acknowledge. Each of the billion particles is the equivalent of 10 galaxies or so, and to save computer time, the calculations leave out factors other than gravity, such as pressure and radiation, that govern galaxy formation. The team also stresses that the computations follow only the invisible "dark matter" that is thought to account for most of cosmic mass, and not the bright galaxies that, in nature, trace the dark mass like campfires dotting the ridgelines of hills. But Michigan's Evrard notes that the largest dark and bright structures are thought to be roughly equivalent.

So far, the team has done calculations on two model universes. One is filled with enough matter to stop cosmic expansion after an infinite time, a condition called omega matter = 1 (see graphics). This is the cosmic recipe most theorists opted for in the past. The other, called the lambda model, is the kind of universe suggested by new measurements of the cosmic expansion rate: one that has an omega matter of 0.3 and a substantial cosmological constant, or large-scale repulsive force (*Science*, 27 February, p. 1298 and 30 January, p. 651).

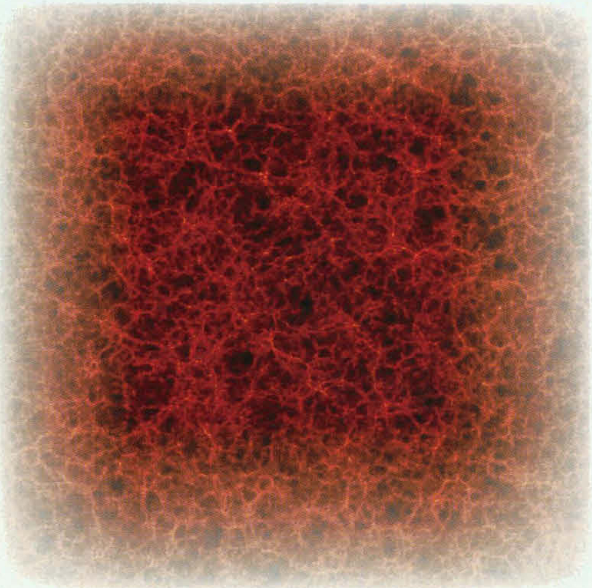
The team then created both "snapshots" of the fully formed universe and views of what an observer would actually see in looking deeper and deeper into the universe from one point. The farther the observer looks, the longer it has taken for light to arrive from that point, so the view gradually moves to earlier times in cosmic history along a wedgelike bundle of lines of sight. Even veteran researchers in the consortium were taken aback by the stunning detail seen in these time-lapse pictures, which were created mostly by Evrard. Says Carlos Frenk of the University of Durham in the U.K., who co-directs the consortium with White, "I was amazed that even at very early times, you see a huge amount of structure"—filaments and walls like the ones that observers have seen in the nearby universe. Agrees Evrard: "You start to pick out subtleties that you wouldn't have imagined. It blows your mind."

So far, the lambda model seems to be a little closer to the real universe. Large clusters of galaxies form earlier in the lambda model than in the omega = 1 version, more in line with observations. Both models have difficulty accounting for some of the most massive and distant clusters seen in the real sky, however.

As cosmologist David Weinberg of Ohio State University in Columbus and others see it, the simulations should be most valuable as a point of comparison for surveys of the real sky such as the Sloan and the Anglo-Australian 2-degree Field (2dF) Survey. In such surveys, explains Richard Ellis of Cambridge University, a co-principal investigator of the 2dF Survey, "it's as if one was conducting an opinion poll but was a bit worried that the sample questioned might be unrepresentative." The new simulations, say Weinberg and Ellis, should help cosmologists distinguish true indicators of the type of universe we live in from statistical flukes. "You have a volume big enough that you can plunk a 'theoretical observer' down in the simulation and create an artificial Sloan survey" to see what kinds of features are typical, says Weinberg, who is a member of the Sloan collaboration.

Already, says Frenk, the simulations are pouring out clues to everything from how often galaxy clusters would tend to clump together into superclusters to the likelihood that we might live in a relatively tenuous "bubble" within the cosmos, as observations are beginning to suggest (*Science*, 15 May, p. 1008). And because the team plans to make its data public, other researchers will be able to make their own journeys through the far reaches of this silicon universe.

–James Glanz



JÖRG COLBERG / MPA

Snapshot. A slice of the present-day universe, as it would look if the speed of light were infinite and existing structures could be seen equally well at any distance.