SPECIAL REPORT

READING THE BLUEPRINTS of CREATION

By Michael A. Strauss

The latest maps of the cosmos have surveyed hundreds of thousands of galaxies, whose clustering has grown from primordial fluctuations

As late as the 1970s, cosmology, the study of the universe as a whole, was a field filled with much speculation but few hard facts. New observations and theoretical work over the past two decades have changed that dramatically. Cosmology has become a rigorous, quantitative branch of astrophysics with a strong theoretical foundation backed by abundant data. The big bang model, which states that almost 14 billion years ago the universe started expanding from a state of extremely high density and temperature, is able to explain galaxy motions, the abundance of hydrogen and helium, and the properties of the cosmic microwave background (CMB), the remnant heat from the expanding and cooling gas.

Cosmologists can now go to the next level and claim an understanding of the formation of structures in the universe. Measurements of the large-scale distribution of galaxies, as mapped by cartography projects such as the ongoing Sloan Digital Sky Survey (SDSS), are in beautiful agreement with theoretical predictions. We currently have a coherent model that tracks the growth of subtle density fluctuations laid down in the early universe to the present richness of the night sky.

The universe around us exhibits structure on all scales. Stars are not scattered uniformly through space; they are grouped into galaxies. Our sun is one of several hundred billion stars in the Milky Way galaxy, a highly flattened disk 100,000 light-years across. The Milky Way, in turn, is one of tens of billions of galaxies in the observable universe. Our nearest large galactic neighbor is about two million light-years away. But galaxies are not randomly sprinkled like raisins in a muffin. Between 5 and 10 percent are grouped into clusters containing up to 1,000 galaxies in a volume a few million light-years across.

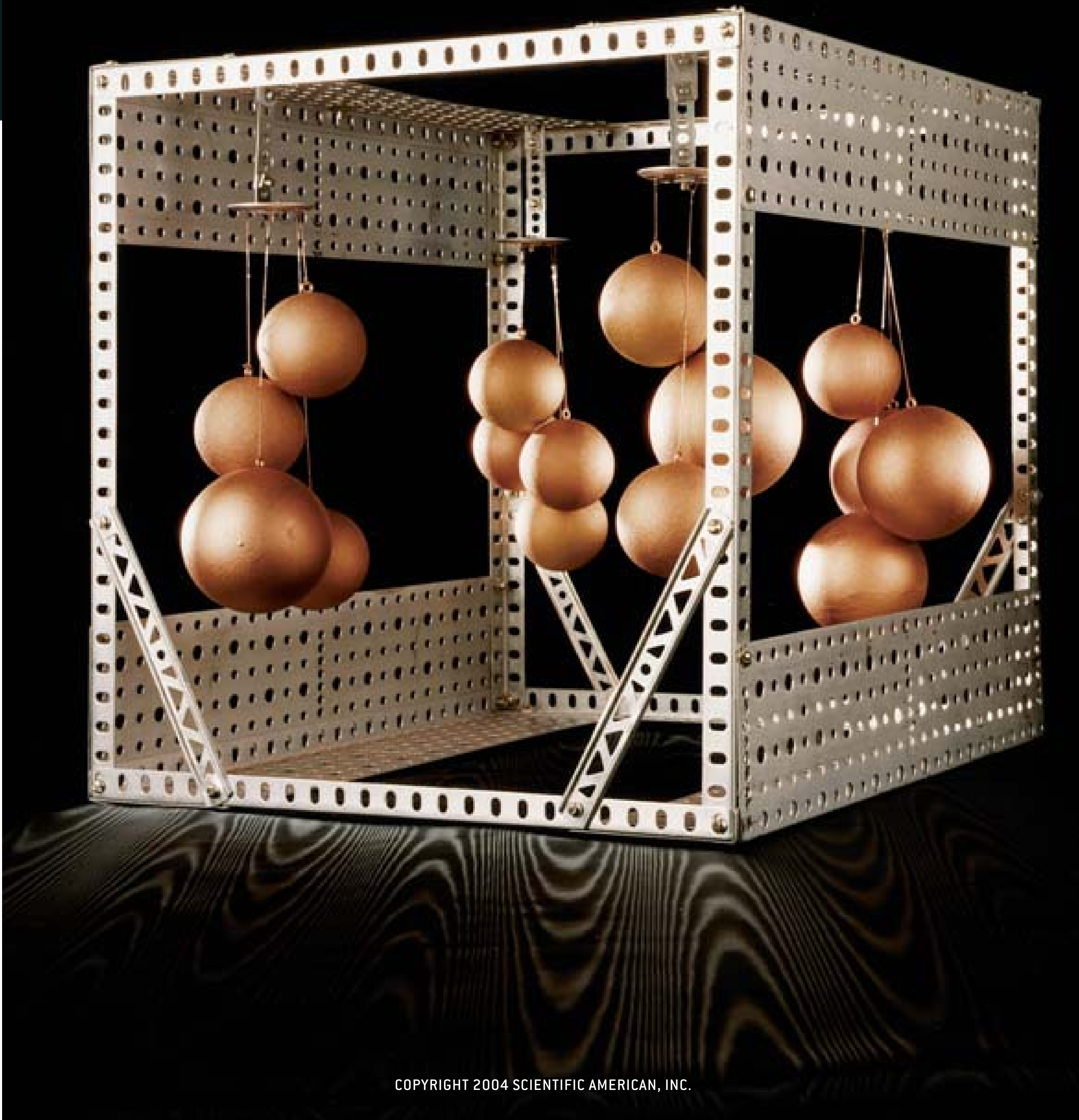
Most astronomers used to think that galaxy clusters were the largest coherent structures in existence. Whereas stars belong to galaxies and many galaxies belong to clusters, the clusters did not seem to be clumped into larger bodies. This picture fit neatly with theorists' understanding of the big bang. When Einstein first applied his general theory of relativity to the universe, he made a dramatic simplifying assumption: the universe, on average, was homogeneous (it had no big lumps) and isotropic (it looked the same in all directions). He called this assumption the cosmological principle, and it underlies all modern scientific models of the universe.

Becoming Aware of Large Structures

TESTING WHETHER the principle applies beyond galaxy clusters requires some depth perception. When you point a telescope at the night sky, the eyepiece reveals stars, planets and galaxies. But without further information, you will not know which objects are small and nearby or large and far away. Fortunately, the telescope can provide that information. For galaxies, the key is that we live in an expanding universe. Galaxies are receding from one another, and the more distant a galaxy is, the faster it is moving away from us. This motion manifests itself as a redshift in the spectrum of the galaxy. The energy of its photons decreases (shifts in wavelength from blue to red) by an amount that depends on its distance. Having established this relation for objects of known distance, researchers use it to study galaxies of unknown distance. They obtain their spectra,

THE UNIVERSE IS HIGHLY STRUCTURED on scales up to a billion light-years or so. Matter is not randomly scattered; gravity has organized it.

DAVID EMMITE PHOTOGRAPHY



determine their redshifts and infer how far away they are.

By the late 1970s, advances in telescope and detector technology made it feasible to carry out extensive redshift surveys of galaxies to create three-dimensional maps of the local cosmos. As a junior in college, I read a *Scientific American* article by Stephen A. Gregory and Laird A. Thompson ["Superclusters and Voids in the Distribution of Galaxies," March 1982] that detailed some of these first 3-D maps. The authors described hints that Einstein's cosmological principle might be wrong: the discovery of coherent structures that were much larger than single clusters, and great voids many tens of millions of light-years across. I was fascinated. This exercise in cosmography, in discovering entirely new structures in the universe, struck me as one of the most exciting things happening in science, and it led me to my present career.

In 1986 Valérie de Lapparent, Margaret J. Geller and John P. Huchra of the Harvard-Smithsonian Center for Astrophysics (CfA) published a map of the distribution of 1,100 galaxies, out of what eventually would be a survey containing 18,000 galaxies. This survey confirmed the richness and ubiquity of large structures. It revealed an unmistakably frothy appearance to the galaxy distribution; galaxies were located along filaments, leaving enormous voids. Among the map's most notable features was a structure dubbed the Great Wall, which stretched 700 million light-years from one edge of the surveyed region to the other. Given that the map did not reveal its end, the full extent of the wall was unknown.

The presence of the Great Wall and the uncertainty about its extent added to the suspicion that the cosmological principle, and therefore our basic theoretical underpinning of the expanding universe, might be incorrect. Was Einstein wrong? Was the universe not homogeneous on average? It was clear that we needed to survey larger volumes to find out.

The big bang paradigm holds that the structure we see in galaxy distribution today grew out of variations present in the almost perfectly smooth early universe. These initial fluctuations were subtle; the density typically varied from one region to another by only one part in 100,000, as measured in the temperature of the cosmic microwave background [see "The Cosmic Symphony," by Wayne Hu and Martin White, on page 44]. If a region of space had a density higher than the average, it had a greater gravitational pull, and thus matter in its vicinity was drawn into it. Similarly, a region of space that was slightly less dense than average lost mass with time. Through this process of gravitational instability, the denser regions eventually became the huge galactic superclusters we see today; the less dense regions became the vast empty voids.

Overview/*Cosmic Structure*

- Astronomers, acting as cosmic cartographers, are creating ever more detailed three-dimensional maps of the locations of galaxies and galaxy clusters. The largest of these projects, the Sloan Digital Sky Survey, is plotting a total of one million galaxies out to a distance of two billion light-years.
- The maps show that galaxies are organized into huge structures, stretching hundreds of millions of light-years. These surveys have quantified the degree of clustering to high precision. The results agree with the clustering expected from extrapolating the cosmic microwave background (CMB) fluctuations to the present. The agreement indicates that astronomers finally have a consistent account of 14 billion years of cosmic evolution.

Running Hot and Cold

ABOUT THE TIME the early redshift surveys were completed, astronomers realized that the story had a twist: the stars and gas we see in galaxies represent just a small fraction (about 2 percent) of the total matter in the universe. The rest of the matter is revealed indirectly through its gravitational effects. Astronomers proposed a variety of models to describe this dark matter. These fell into two broad categories, cold and hot, and the difference is crucial to the evolution of structure.

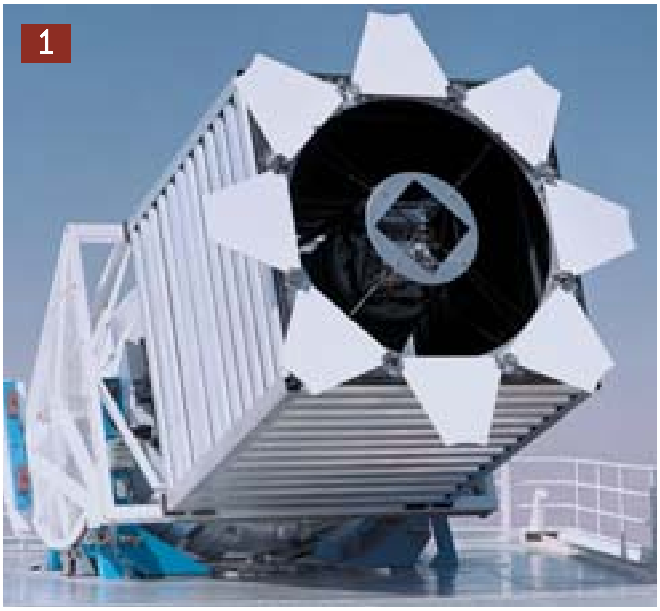
In the cold dark matter scenario, suggested by P. James E. Peebles of Princeton University and others, the first structures to form were relatively small objects such as galaxies and pieces of galaxies. As time went on, gravity brought these together in ever larger structures. In this model, the Great Wall formed relatively recently. In the hot dark matter scenario, posited by Yakov B. Zel'dovich and his colleagues at Moscow State University, dark matter moved sufficiently quickly in the early universe to smooth out any clustering on small scales. The first things to form were large sheets and filaments tens or hundreds of millions of light-years in extent, which only later fragmented to form galaxies. In other words, the Great Wall is ancient.

Thus, the next generation of surveys would not just test Einstein's cosmological principle and identify the largest structures in the universe; it would also probe the nature of dark matter. One such survey was conducted from 1988 to 1994 by Stephen A. Shectman of the Carnegie Institution of Washington and his collaborators using the Las Campanas 2.5-meter telescope in Chile [see "Mapping the Universe," by Stephen D. Landy; SCIENTIFIC AMERICAN, June 1999]. The survey contained 26,418 galaxy redshifts and covered an appreciably larger volume than the original CfA survey. As team member Robert P. Kirshner of the CfA phrased it, the Las Campanas survey found "the end of greatness." It revealed a galaxy distribution similar to that of the CfA survey but saw no structures much larger than the Great Wall. Einstein's cosmological principle appeared to hold: the cosmos is homogeneous and isotropic over vast distances.

The Las Campanas survey was still not large enough to be definitive, however. It said nothing about what was happening in regions of space one to two billion light-years across. It is on these largest scales that clustering is the easiest to interpret theoretically yet the hardest to measure observationally. The variations in galaxy numbers over such a volume are subtle, and it is easy to introduce errors into the sample; artifacts of the selection procedure might masquerade as clustering.

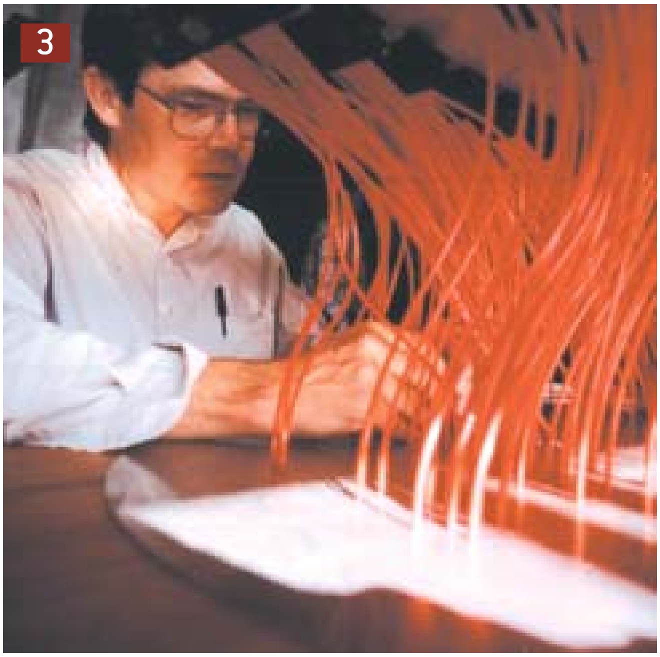
HOW TO SURVEY THE COSMOS IN FOUR NOT-SO-EASY STEPS

THE SLOAN DIGITAL SKY SURVEY, the most advanced of the current generation of astronomical surveys, is compiling an atlas of a quarter of the sky. It will take five years, using a dedicated 2.5-meter telescope atop Apache Point in New Mexico.

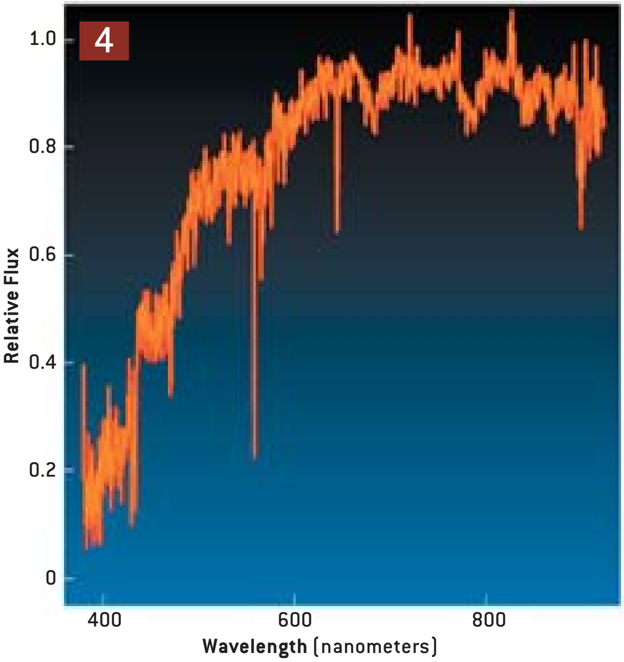


THE TELESCOPE operates in camera mode on clear nights, taking pictures through five color filters at the rate of 20 square degrees an hour—netting millions of celestial bodies per night.

GALAXIES and other objects are identified by software and selected for follow-up spectroscopy. The object shown here is the spiral galaxy UGC 03214 in the constellation Orion.



OPTICAL FIBERS are plugged into a metal plate with 640 holes. Each fiber channels light from a celestial body to a spectrograph, which operates when the sky is not so clear.

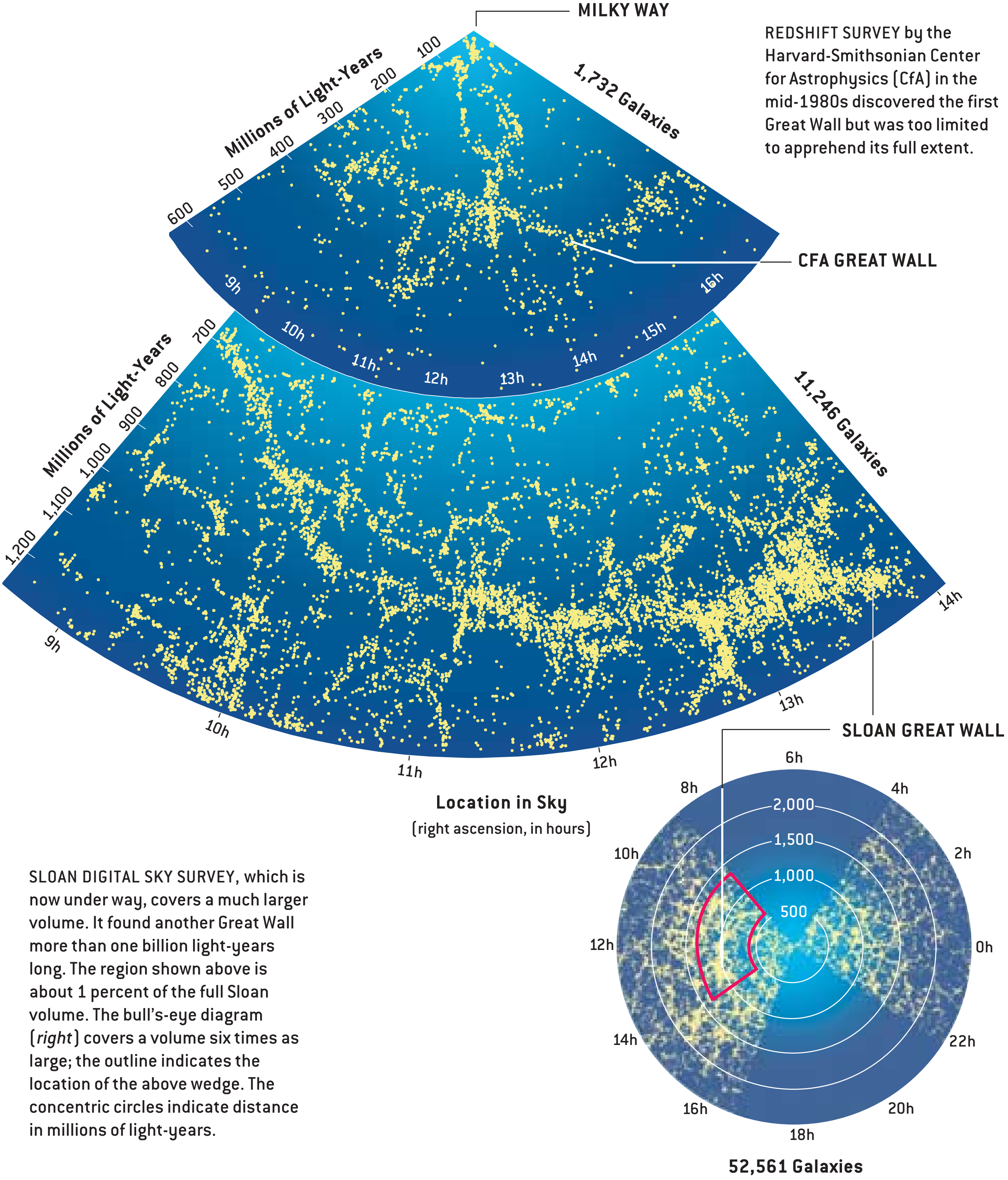


THE SPECTRA THAT RESULT provide a precise way to classify objects. From them, astronomers also determine the redshifts, hence distances, of the objects.

SDSS COLLABORATION

COSMIC MAPS

THESE WEDGE-SHAPED FIGURES show the distribution of galaxies (*dots*) in two volumes of space. The third dimension, which spans an angle of several degrees, has been flattened. The figures reveal two dramatic "Great Walls" containing thousands of galaxies each, as well as filaments and voids at all scales.



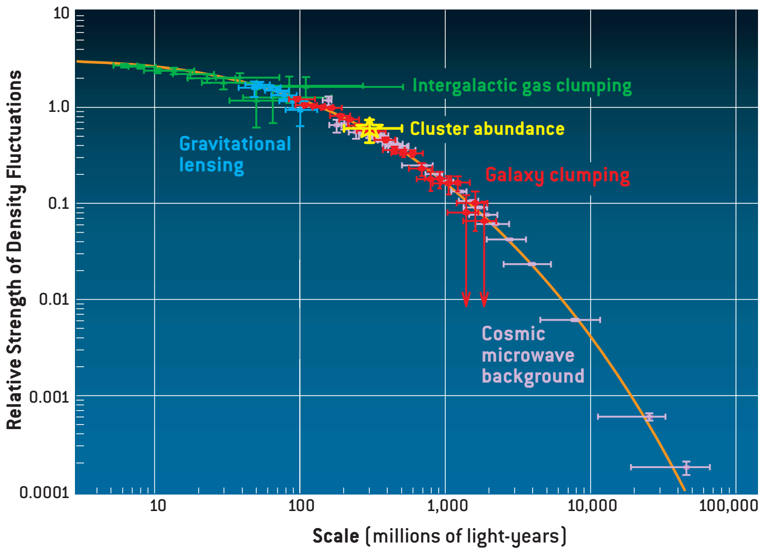
REDSHIFT SURVEY by the Harvard-Smithsonian Center for Astrophysics (CfA) in the mid-1980s discovered the first Great Wall but was too limited to apprehend its full extent.

SLOAN DIGITAL SKY SURVEY, which is now under way, covers a much larger volume. It found another Great Wall more than one billion light-years long. The region shown above is about 1 percent of the full Sloan volume. The bull's-eye diagram (*right*) covers a volume six times as large; the outline indicates the location of the above wedge. The concentric circles indicate distance in millions of light-years.

BRYAN CHRISTIE DESIGN; SOURCES: J. RICHARD GOTT AND MARIO JURIĆ *Princeton University* (*wedge*); SDSS COLLABORATION (*bull's-eye*)

OVERALL DISTRIBUTION OF COSMIC STRUCTURE

THE MAPS produced by galaxy surveys can be boiled down to a power spectrum, which shows the fractional density variation (*vertical axis*) from one position to another in regions of different sizes (*horizontal axis*). Other data—cosmic microwave background, gravitational lensing, galaxy-cluster surveys, hydrogen gas clouds—can be plotted in the same way. They follow the same universal curve (*solid line*). The relative fluctuations approach zero, substantiating Einstein's cosmological principle. The arrows represent upper limits.



BRYAN CHRISTIE DESIGN; SOURCE: SLOAN DIGITAL SKY SURVEY

Astronomers, for example, typically choose all galaxies brighter than a certain value to be included in a given redshift survey. If they overestimate galaxy brightnesses in one part of the sky, the sample will have too many galaxies in that region, yielding a false measurement of clustering. Thus, a definitive redshift survey must not only cover a huge volume, it must be exquisitely calibrated.

On a Clear Night…

IN THE LATE 1980s James E. Gunn of Princeton, Richard G. Kron and Donald G. York of the University of Chicago and others began a collaboration to do the problem right. That is, they sought to measure the distribution of galaxies in the largest volume to date, with careful control of calibration. About a decade later the Sloan Digital Sky Survey, an $80-million, 200-astronomer collaboration, started operation. The SDSS features a special-purpose telescope with a 2.5-meter-wide primary mirror. The telescope operates in two modes. On the most pristine nights, it uses a wide-field camera to take carefully calibrated pictures of the night sky in five broad wavebands. The camera uses CCDs, highly sensitive electronic detectors whose response can be calibrated with an accuracy of 1 percent.

On nights with moonshine or mild cloud cover, the telescope instead uses a pair of spectrographs to obtain spectra, and therefore redshifts, of 608 objects at a time. For reference, the device also takes spectra of 32 blank patches of sky. Unlike traditional telescopes, for which nights are parceled out among many scientific programs, this telescope is devoted solely to the survey, every night for five years. The project is now approaching the halfway point in its goal of measuring one million galaxy and quasar redshifts. As a midterm report, my colleagues and I recently completed an analysis of the first 200,000 galaxies with redshifts.

In a parallel effort, a team of Australian and British astronomers built a spectrograph for the 3.9-meter Anglo-Australian Telescope, capable of measuring the spectra of 400 objects at a time over a field of view two degrees on a side (thus earning the name "Two Degree Field," or 2dF). The 2dF team worked from galaxy catalogues drawn from carefully calibrated and electronically scanned photographic atlases that were already available. Now complete, the survey measured the redshifts of 221,414 galaxies over a period of five years.

Our surveys describe the distribution of galaxies. They do not see dark matter, which constitutes the bulk of the mass of the universe. Researchers have no reason to assume that the distribution of galaxies is the same as the distribution of dark matter. For example, galaxies might tend to form only in regions that contain an above-average density of dark matter—a scenario astronomers refer to as biasing.

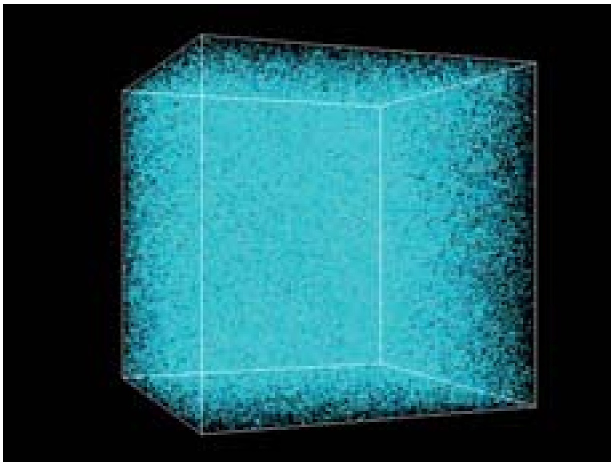
By analyzing previous generations of redshift surveys, my colleagues and I had shown that the galaxy and dark matter distributions were closely related, but we were unable to distinguish between simple models of bias and the unbiased case. More recently Licia Verde of the University of Pennsylvania and her colleagues used the 2dF galaxy redshift survey to measure triplets of galaxies. It turns out that the number of these trios

THE AUTHOR

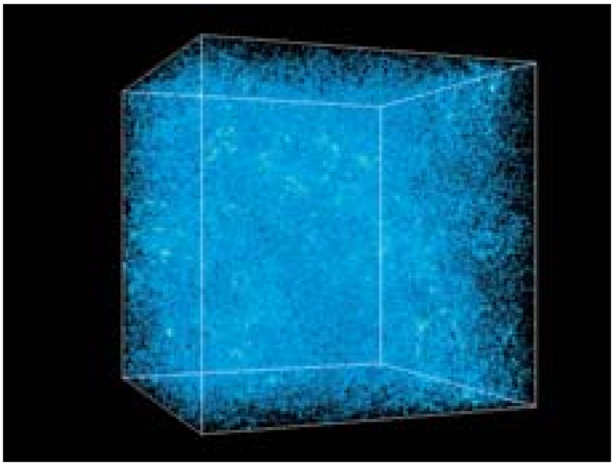
MICHAEL A. STRAUSS is deputy project scientist and project spokesperson for the Sloan Digital Sky Survey, an effort to make a complete map of a quarter of the sky. He received a Ph.D. in physics from the University of California, Berkeley, did postdoctoral work at the California Institute of Technology and at the Institute for Advanced Study in Princeton, N.J., and now holds a faculty position at Princeton University. He thanks his Sloan project colleagues for a fabulous data set. Strauss was featured in the September 2002 issue of *New Jersey Monthly* as having one of the best jobs in the state of New Jersey.

BUILDING A UNIVERSE

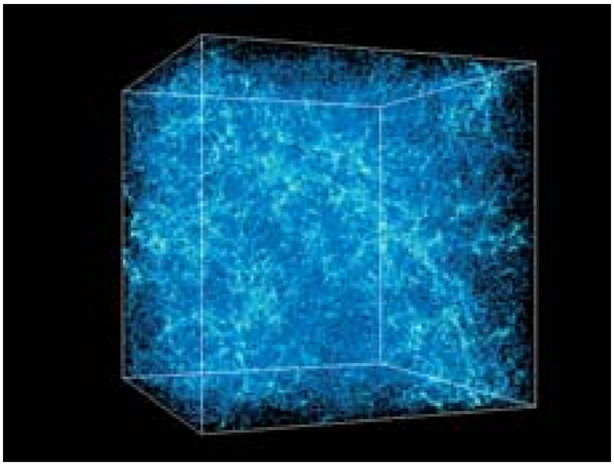
TO CONNECT THE CLUMPING of matter today (revealed by Sloan and other mapping projects) with the clumping of matter in the early universe (revealed by observations of the cosmic microwave background radiation, or CMB), cosmologists run computer simulations. Each frame is a snapshot at a time after the onset of the big bang expansion. Because the universe is expanding, the frames are not to scale: the first one is about five million light-years across, the last one about 140 million light-years across. Dots represent matter. The simulation was performed at the National Center for Supercomputer Applications (the full movie is available at cfcp.uchicago.edu/lss/filaments.html).



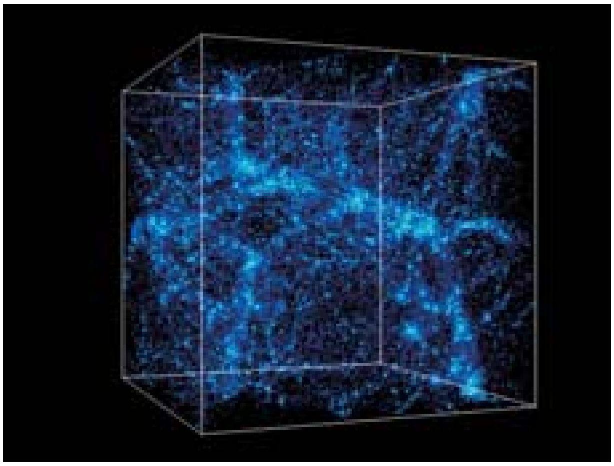
120 MILLION YEARS: Early on, matter was spread out in a nearly uniform sea with subtle undulations.



490 MILLION YEARS: Dense regions gained material at the expense of less dense ones. The first galaxies formed.



1.2 BILLION YEARS: Over time, gravity pulled matter into vast filaments and emptied the intervening voids.



13.7 BILLION YEARS (TODAY): The growth of large structures has ceased because cosmic acceleration counteracts clumping.

ANDREY KRAVTSOV *University of Chicago* AND ANATOLY KLYPIN *New Mexico State University*

depends on the total mass, dark matter included. The researchers found that the galaxy distribution is essentially unbiased: the density field of galaxies is the same as that of the dark matter, which means that the galaxy surveys accurately reflect the overall arrangement of matter in the cosmos.

The Power of the Power Spectrum

WITH THIS CAVEAT ADDRESSED, cosmologists can interpret the galaxy maps. Among the most useful statistical tools to describe galaxy clustering is the power spectrum. Imagine placing a series of spheres of a given radius (say, 40 million light-years) at random in the universe and counting the number of galaxies in each one. Because galaxies are clustered, that number will vary substantially from one sphere to another. The variation in the number of galaxies is a measure of the lumpiness of the galaxy distribution on a scale, in this case, of 40 million light-years. Cosmologists repeat the exercise with spheres of various radii to measure this lumpiness at different scales.

An analogy is to express a complex sound in terms of the contributions from sound waves of different wavelengths. A graphic equalizer on a home audio system can perform this function: it shows how loud the deep bass notes (of very long wavelength) are, how loud the treble (of shorter wavelength) is, and so on. In a live concert, a person with a musically trained ear can easily pick out the piccolo from the bassoon. Cosmologists do the same thing with the distribution of galaxies. The relative amount of structure on large and small scales is a powerful cosmological probe.

The power spectrum has been measured by both the 2dF and Sloan teams, with consistent results. The first thing to note is that the fluctuations are weaker as one proceeds to larger scales [*see illustration on page 59*]. Weak fluctuations mean that the galaxy distribution is very close to homogeneous, exactly as Einstein's cosmological principle requires.

Second, the power spectrum, when plotted on a logarithmic scale, does not follow a straight line. The deviation from straightness is confirmation that the dynamics of the universe have changed with time. From other observations, astronomers have concluded that the energy density of the universe is dominated by matter and a mysterious component known as dark energy. Photons, their energy sapped by cosmic expansion, are negligible. Extrapolating backward in time, however, photons dominated when the universe was less than 75,000 years old. When photons ruled, gravity did not cause fluctuations to grow with time the same way they do today. That, in turn, caused the power spectrum to behave differently on the largest scales (more than about 1.2 billion light-years).

The exact scale of this deviation provides a measure of the total density of matter in the universe, and the result—roughly 2.5×10^{-27} kilogram per cubic meter of space—agrees with the value from other measurements. Finally, the combination of these results strongly suggests that the dark matter is all of the cold variety. Hot dark matter would smooth out the fluctuations in the galaxy distribution on smaller scales, and that is not seen.

The fluctuations we observed in the galaxy distribution on large scales should simply be an amplified version of those of the early universe. These early fluctuations are apparent directly in the CMB, so we can directly compare the CMB and galaxy power spectra. Amazingly, we get consistent answers from these two approaches. On scales approaching one billion light-years, the galaxy density fluctuates by about one part in 10. The CMB reveals fluctuations of one part in 100,000, which, when extrapolated to the present, are in beautiful agreement. This gives us confidence that our cosmological picture—big bang, gravitational instability and all—is actually correct.

The Future of Large-Scale Structure Studies

THE MAIN SDSS GALAXY SURVEY probes the structure of the cosmos on scales from 100 million to more than one billion light-years. To probe yet larger scales, SDSS has a second, auxiliary sample of extremely luminous galaxies that extends more than five billion light-years away. For smaller scales, a third sample looks at absorption lines in the spectra of distant quasars, whose light passes through a dense network of clouds of hydrogen gas not yet formed into galaxies.

With these data, cosmologists are working to make an even tighter connection between cosmic structures (seen today and the not so distant past) and the CMB (which probes cosmic structures in the very early universe). In particular, the power spectrum of the microwave background shows a series of distinctive bumps, which reflect the relative amounts of dark and ordinary matter. Researchers hope to find the equivalent bumps in the present-day power spectrum. If they do, it will be further confirmation that the fluctuations observed today evolved directly from those seen in the early universe.

Another way to trace the development of structures over time is to probe the distribution of more distant galaxies—looking to great distances is looking back in time. The dark matter at those early times should be weakly clustered because gravitational instability had not yet had as much time to operate. But surveys carried out with the European Southern Observatory's Very Large Telescope in Chile and the Keck Observatory in Hawaii show that tremendously distant galaxies are just as clustered as today and are arranged in the same filamentary, bubbly structures that nearby galaxies are. This is odd. Unlike today's galaxies, which follow the dark matter, these early galaxies must be much more strongly clustered than the underlying dark matter is. This pattern is an important clue to how galaxies formed.

Researchers are close to a complete understanding of the development of the structure of the cosmos, from undulations in the primordial plasma to the bright galaxy clusters of the modern universe. That said, their work is cut out for them in the coming years. What exactly is the mechanism that gave rise to the initial fluctuations in the microwave background? How exactly did the galaxies form? Why do they have the properties that they do? And could it have been any other way—could one imagine a universe with fluctuations that started out with much higher or lower amplitudes? These are among the big questions that perhaps a high school or college student reading this article will be inspired to tackle.

MORE TO EXPLORE

Cosmological Physics. John A. Peacock. Cambridge University Press, 1998.

Cosmology: The Science of the Universe. Second edition. Edward Harrison. Cambridge University Press, 2000.

The 2dF Galaxy Redshift Survey: The Power Spectrum and the Matter Content of the Universe. Will J. Percival et al. in *Monthly Notices of the Royal Astronomical Society,* Vol. 327, No. 4, pages 1297–1306; November 2001. Available online at **arXiv.org/abs/astro-ph/0105252**

From Here to Eternity. Valerie Jamieson in *New Scientist,* Vol. 180, No. 2422, pages 36–39; November 22, 2003. The centerfold map is also available at **www.astro.princeton.edu/~mjuric/universe/**

The Three-Dimensional Power Spectrum of Galaxies from the Sloan Digital Sky Survey. Max Tegmark et al. in *Astrophysical Journal* (in press). **arXiv.org/abs/astro-ph/0310725**

The official Web site of the Sloan Digital Sky Survey is **www.sdss.org**
The official Web site of the 2dF Galaxy Redshift Survey is **msowww.anu.edu.au/2dFGRS**