ultraviolet wavelengths, creating a drop in the ultraviolet part of the spectrum called the Lyman break. Using several different telescopes, the team has been screening galaxies for the Lyman break and therefore for redshifts beyond 3.0.

Starting with objects near quasars, then searching elsewhere in the sky, they found over 100 candidates. Using the Keck, they collected full spectra for 18 of them. The Lyman-break galaxies have redshifts between 3.0 and 3.5 and are shaped, says Giavalisco, "like blobs, compact blobs," just the size of a spiral galaxy's bulge or an elliptical's central core. They're forming stars at the same high rate as the irregular blues. "There's no reason to believe they're different populations," says Simon White of the Max Planck Institute for Astrophysics in Garching, Germany. And, says Steidel, "the number per unit volume closely matches the numbers of bright galaxies today." Craig Hogan, a theorist at the University of Washington, Seattle, concludes, "Wait 14 billion years, and they'd look like today's galaxies."

The tidiest history of galaxies would draw a straight line from the Lyman-break galaxies through the irregular blues to the local spirals and ellipticals. That's plausible, says Lilly. But he cautions that this story line is far from certain, because there are still so few points along it. "We desperately need some property to see so we know what changes into what," he says. "It's a shame galaxies don't come with great big flags on them."

Even though astronomers can't be sure of the story so far, they have no trouble extrapolating it into the future. Between a redshift of 1.0 and the present, galaxies have drawn in all the gas that once filled the space between them and turned it into stars. "In the present-day universe, things are running out of gas," says White. "It began with everything in gas and ends up with everything in stars." Eventually, Peebles says, "stars stop shining because there's no gas left." Cowie has a way with words: "The universe is moving into a dark valley. It's an expiring universe."

Until it does expire, however, observers will stay at work. Observations of the Lyman-break galaxies at the farthest distances are ongoing. Surveys of galaxies in the universe's adolescence are pushing to deeper redshifts. Work on the Hubble Deep Field survey, which Williams released to the astronomical community for analysis, has barely begun. "It's a question of seeing what there is and making sense of it," Lilly says. "We have these simple-minded ideas and won't be surprised if it's all different than we think."

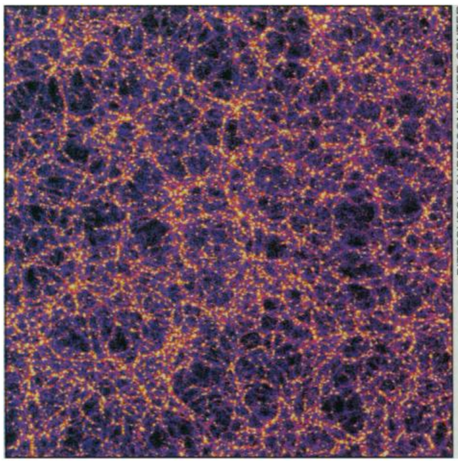
–Ann Finkbeiner

Ann Finkbeiner teaches writing at Johns Hopkins University.

STRUCTURE FORMATION

Galaxy Surveys Seek the Architecture of the Cosmos

Cosmologically speaking, astronomers are still getting to know the neighborhood. Like a family gazing from its picture window at the porch lights of a strange new suburb, they have gradually picked out the brightest galaxies within a few hundred million light-years of the Milky Way. Now they are ready to explore more systematically, by carrying out the most comprehensive and sensitive "sky surveys" ever, reaching billions of light-years into space to catalog millions of galaxies and fix their positions. Not only will these efforts provide the first reliable maps of our part of the universe; they should also help cosmologists understand how it was laid out: how the clumps and filigrees of galaxy clusters seen in the sky took shape from tiny fluctuations in the density of the early universe.



PITTSBURGH SUPERCOMPUTER CENTER

Fabric of the cosmos. A supercomputer simulation of a 300 million light-year slice shows how galaxies would be expected to cluster in a critical-density universe dominated by cold dark matter.

Like the ongoing measurements of the cosmic microwave background, which gives a snapshot of those wrinkles early in cosmic history (see p. 1431), the galaxy surveys are tracing the fingerprints of the big bang. "The fact that [both measurements] are going to be coming in simultaneously makes this an extraordinary epoch," says Paul Steinhardt, a cosmologist at the University of Pennsylvania: "humanity's first view of the farthest distances and earliest times available, along with the finest, most detailed map of what the universe looks like today."

The patterns revealed in the cosmic surveys will help test theories of the big bang's immediate aftermath, when the wrinkles formed. They will also help cosmologists gauge the universe's complement of unseen "dark matter," whose gravitational influence is believed to have shaped the growth of those wrinkles into today's great clusters, filaments, and walls of galaxies. The power of these surveys will only increase when their scale becomes large enough to overlap with measurements of the microwave background. And along the way to addressing cosmological issues, the surveys will also sharpen astronomers' knowledge of how individual galaxies evolved and why some of them had short, brilliant lives in the early universe as quasars.

These efforts to survey the cosmos owe as much to recent technological developments as to today's burning scientific questions. Advances in light detection, computers, telescope design, robotics, and spectroscopy mean that wide-angle images of the sky can be obtained up to 10 million times faster than was possible 2 or 3 decades ago, says George Lake of the University of Washington, Seattle, a member of the multi-institutional Sloan Digital Sky Survey, by far the largest and most ambitious of the forthcoming surveys. Many of these advances are reaching their limits, he says, so "now's the time to go out and do it. It's not going to get any better by waiting."

What's not new is the urge to map our part of the cosmos. Astronomers have understood the value of doing so for decades, ever since the National Geographic Society–Palomar Observatory Sky Survey (POSS I) of the 1950s used Palomar's 1.2-meter Oschin Schmidt telescope to make about 1000 14-inch photographic plates of the northern sky in two different color bands. Originally seen as a way "to pick out interesting objects for [Palomar's] 200-inch telescope," says Neill Reid of the California Institute of Technology (Caltech), which operates the observatory, the database soon became part of the intellectual bedrock of astronomy.

It was by eyeball examination of the POSS I plates, for example, that the astronomer George Abell produced the first catalogs of galaxy clusters in the 1950s and 1960s. Neta Bahcall of Princeton University and collaborators used the catalog in the early 1980s to show that the clusters themselves clump together on larger spatial scales than predicted for a universe with a composition then favored by some theorists: one that contains enough "cold dark matter" (CDM)—heavy, exotic, elementary particles—for gravity to arrest its expansion, given infinite time. Researchers at Caltech are now redoing the Palomar survey, taking advantage of improved photographic technology and optics. POSS II, as it's called, also benefits from scanning technology that can digitize the images, making them widely available and amenable to computer analysis.

Looking in depth. Such photographic surveys have the advantage of being fast enough to cover huge swaths of sky, but they lack one essential feature: depth. To transform a flat image into a three-dimensional map, astronomers must take an individual spectrum for each galaxy. Because the universe is expanding, spectral peaks from more remote galaxies are shifted farther toward the red end of the spectrum, yielding an approximate distance measure.

Collecting and analyzing spectra is a painstaking process, but redshift maps can reveal features that are invisible in simple images. In the mid-1980s, for example, Margaret Geller and John Huchra at the Harvard-Smithsonian Center for Astrophysics (CfA) compiled three-dimensional maps for sections of the northern sky using the 60-inch telescope on Mount Hopkins in Arizona. The maps revealed the largest structure astronomers had ever seen: the Great Wall, a collection of galaxies stretching over several hundred million light-years. The CfA survey also showed that the cosmos is riddled with "voids"—huge regions nearly empty of galaxies.

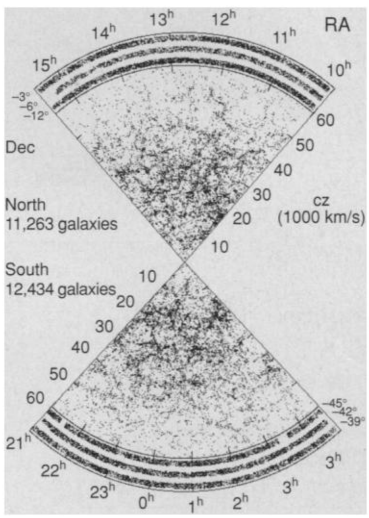
Both features presented a challenge to CDM models and helped spur the development of variants, such as model universes that contain only a fraction of the critical mass density or include some "hot dark matter"—fast-moving particles such as massive neutrinos—along with the cold dark matter. Such models would skew structure formation toward large scales. But to see how well the models' predictions about structure match the observed universe, cosmologists wanted to know how widespread these giant structures are.

To help answer this question, a team called the Southern Sky Redshift Survey (SSRS2), led by Luiz da Costa at the European Southern Observatory in Garching, Germany, used several telescopes to map several thousand galaxies as far as a few hundred million light-years away. When combined with the larger CfA database, the SSRS2 data showed cosmic structure on the largest sizes the observations could probe, including a smaller Southern Wall. Concludes da Costa: "Voids and walls are common features of the galaxy distribution."

A still more extensive survey is now echoing some of those conclusions. The 6-year project at the Las Campanas Observatory in Chile has taken redshifts of about 26,000 galaxies in half a dozen pie-shaped slices of sky out to distances several times greater than in the CfA and SSRS2 surveys. Huan Lin, a team member who is now at the University of Toronto, says that the clustering properties of galaxies on hundred-million-light-year scales now seems to favor the CDM variants.

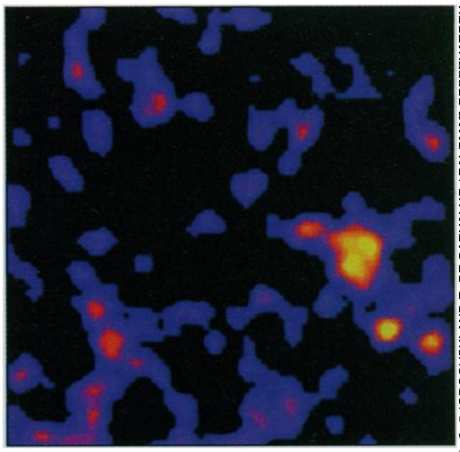
But although the Las Campanas data could still yield surprises, the only way to choose a more specific model of how structure formed, says Lin, is to chart more of the cosmos, in much greater detail. A more precise map could also help pin down the spectrum of the clustering, possibly yielding clues to the earliest instants of the big bang. To do all of this, researchers from eight institutions—Princeton University, the Institute for Advanced Study, the University of Chicago, Fermi National Accelerator Laboratory, Johns Hopkins University, the University of Washington, the U.S. Naval Observatory, and the Japanese Promotion Group—designed the Sloan survey, which will catalog dozens of times more galaxy redshifts than any of its predecessors. The goal of the 5-year effort, says Bahcall, "is to have, for the first time ever, a really accurate, three-dimensional map of the [local] universe."

The project, scheduled to begin its first tests later this year, will rely on a dedicated, 2.5-meter telescope at Apache Point, New Mexico. The specially built telescope will be perched above a mountainside, away from warm air masses along the ground that can cause stars to twinkle, and will be protected by wind baffles rather than the traditional dome to reduce thermal gradients even further. Like other recent surveys, the Sloan will use charge-coupled devices (CCDs)—exquisitely sensitive, solid-state devices that convert photons to electrical charge—to create digital images directly. And it will combine them with a high level of automation.



Big cheese. Distribution of galaxies and voids out to several hundred million light-years, from the Las Campanas Redshift Survey.

The first step in the operation, says Rich Kron of the University of Chicago and Fermilab, "is fairly straightforward—you just turn on the CCDs and let the data flow." The telescope's direction will stay nearly fixed for each night's observations, letting Earth's rotation sweep light across five rows of CCDs sensitive to different wavelength bands. From these scans, which will eventually capture several hundred million celestial objects, a computer will pick out the ones fuzzy enough to be galaxies. The telescope will then return to the same area of sky and take spectra of the galaxies—about 600 at once, through fiber optics mounted on plates in the focal plane.



Populating the sky. A computer map of galaxy densities, from the Digitized Palomar Sky Survey, reveals clustering.

The result, after 5 years, should be a million galaxy redshifts from an area covering a quarter of the sky and extending out several billion light-years. "From this massive attack, we intend to address the distributions of those objects in space at a correspondingly refined level," says Kron. Instead of finding just a few of the immense structures to which theorists are comparing their models, the Sloan should provide them in bulk—providing the previous finds were not statistical flukes.

The Sloan will be complemented by the British and Australian 2dF Survey, a slightly less ambitious project at the 3.9-meter Anglo-Australian Telescope that will be completed in 1998. The 2dF will cover parts of the sky inaccessible to the Sloan and will be able to pick up fainter galaxies because of its telescope's larger aperture. Also under way are many other smaller or more focused surveys, in the optical, infrared, radio, and x-ray wavelength bands. Among them are other facets of the Sloan and 2dF, which aim to collect redshifts for hundreds of thousands of quasars—galaxylike beacons in the early universe that may have their own story to tell about cosmic structure.

Together, says Matthew Colless of the Mount Stromlo and Siding Springs Observatory in Australia, a 2dF participant, these new views of the sky will address "the most pressing and important questions of cosmology—from the mass of the universe, through the nature of the dark matter, to the formation and evolution of galaxies." They should also give us a much better picture of our cosmic neighborhood.

–James Glanz