swirls around the South Pole, allowing them to gather 10 to 30 times as much data as current balloon experiments, which fly for one night only. Several such experiments are planned for the next 2 years.

In the end, however, CMB experimentalists will have to take their instruments into space again. Testing the various models and extracting precise values of the cosmological parameters requires mapping the fluctuations over the entire sky, at scales from a few tenths of a degree on up. "You need the stability of space for that," says Page. "The environment just changes too much for that to be possible from a balloon or the ground."

Such all-sky maps are only a matter of time. In April NASA selected the Microwave Anisotropy Probe (MAP) as one of the first two spacecraft to fly in its new MIDEX series of low-cost missions. Two weeks later, the European Space Agency announced its own cosmic microwave mission, COBRAS/SAMBA (*Science*, 3 May, p. 642).

MAP, which should fly first if all goes well, will cost $70 million and will be built primarily by researchers from Princeton and Goddard. Whereas COBE mapped the sky from 7 degrees on up and was able to resolve perhaps 5000 independent patches on the sky, says Kosowsky, MAP will work from 0.3 degrees upward and should be able to resolve in the neighborhood of a million distinct points. "It will be like looking down on the surface of the Earth from space," he says, "and instead of seeing small bumps where there are mountain ranges, you will now be able to pick out individual mountains."

MAP will have the advantage of 15 months of observing time and an unprecedented vantage point: a position in space, known as the second Lagrange point, which is 1.5 million kilometers from Earth, in a direction opposite the sun. "It is more nearly a solar orbit than an Earth orbit," says Berkeley's Richards, "and the benefit is that the Earth looks like a little tiny pea way off there on the horizon, whereas for COBE, the Earth filled almost half the solid angle. So radiation from the Earth falling on the craft is reduced by an enormous factor."

As presently scheduled MAP should be at its vantage point by 2001. Then the microwave background and the key parameters of the universe should start coming into focus. And the focus should get even sharper when COBRAS/SAMBA, which will map even smaller scales from the same vantage point, begins delivering data 3 years later. "One of the great areas of hubris that physicists have is to think they're going to actually crack the problem of formation and structure of the universe," says Richard Bond of the Canadian Institute for Theoretical Astrophysics in Toronto. "We need some humility approaching this subject, but everything looks quite good so far."

–Gary Taubes

GALAXY FORMATION

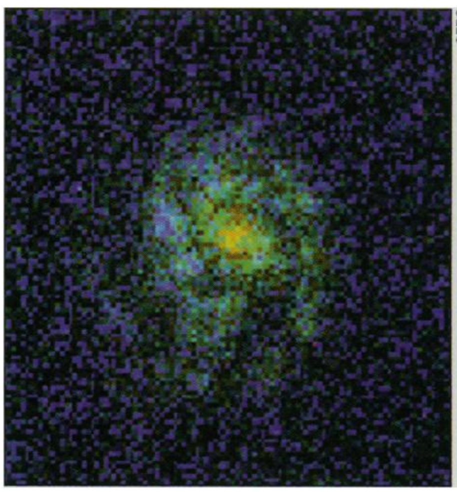
From Snapshots of Distant Galaxies, a History Emerges

Galaxies are the universe's atoms. They're its basic packages of mass, and the bricks of its large-scale architecture. But how the universe got its galaxies has so far been mostly an ingenious just-so story. Astronomers have had little evidence with which to write the galaxies' history from the featureless gas of the early universe through the mature, stately spirals and ellipticals of today.

They did have some clues. They had seen shadows in the light from quasars—beacons shining at the far edge of the universe—created by what seemed to be distant, ancient, infant galaxies lying along the line of sight. Large surveys of the sky had also shown tribes of faint blue galaxies that might be galactic adolescents. But all these galaxies were so faint that astronomers could not make out their shapes or, in many cases, measure their distances and ages, leaving would-be historians with little to go on. In the last couple of years, however, the sharpened vision of the Hubble Space Telescope (HST), the incomparable light-gathering ability of the 10-meter Keck telescope in Hawaii, and new spectrographs that take spectra of many galaxies simultaneously have started to fill in the picture.

With these new tools, several large teams have surveyed distant galaxies in numbers great enough to provide snapshots of certain stages in their evolution. "This is a terribly exciting time in this field," says Simon Lilly of the University of Toronto, one of the surveyors. "The complete picture might just be coming within grasp."

For now, this history has gaps, loose ends, and subplots, but its outline is clear. Early on, maybe 100 million years after the beginning, clouds of gas collapsed to form galaxies of all sizes. The ancient cores of present-day galaxies—the quasar shadows—took shape over the next billion years. They then merged and pulled in additional gas until they formed bigger galaxies, lumpy and peculiar and brilliant with newborn stars—faint blue galaxies seen in the surveys—and the universe was the brightest it's ever been. As the universe expanded, the galaxies grew farther apart, and several billion years after the beginning, gradually stabilized into symmetrical shapes, forming stars more slowly or not at all. By now the gas in the universe has mostly turned into stars. Little gas means few new stars, and the galaxies, along with the universe and many of us, are going on past glory. Says James Peebles of Princeton University, "Things are running down."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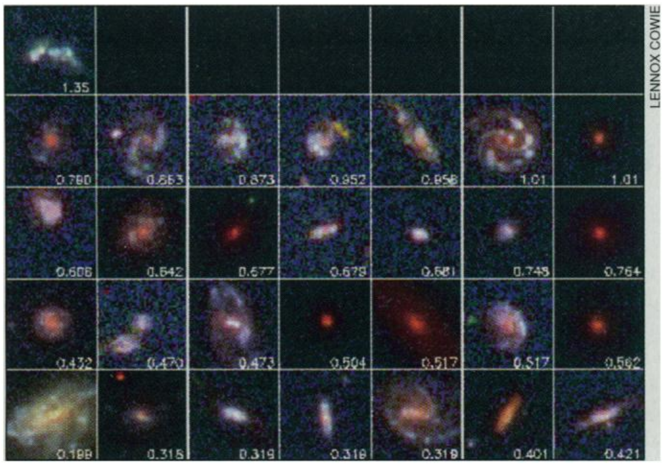
Early portrait. A spiral galaxy with knots of star formation, seen by the Hubble Space Telescope when the universe was half its present age.

Until a few years ago, astronomers were well acquainted only with galaxies in our neighborhood: the spirals, with central bulges full of old, cool, red stars and disks populated by young, hot, blue stars; and the ellipticals, with stars as red and old as those in the spirals' bulges. Then in the 1980s, observers found a sprinkling of faint galaxies that were brightest in blue wavelengths. The galaxies, then called the faint blues, were blue because their stars were young; their faintness might have been intrinsic, or they might have been bright galaxies seen from a great distance. If the latter, they might be the young, distant ancestors of the local galaxies.

To help settle the issue, astronomers needed to measure the distances to these faint blues. A galaxy's distance is calculated from its spectrum. Because all galaxies recede from us as the universe expands, we see their light Doppler-shifted to longer, redder wavelengths. The larger this so-called redshift in a galaxy's spectrum, the farther away the galaxy. In the early 1990s, teams using new spectrographs and larger telescopes began systematically surveying the faint blues.

A British-Australian team—Karl Glazebrook, now at the Anglo-Australian Observatory in Sydney; Richard Ellis and Nial



Lumpy adolescents. An atlas of galaxies, ordered by redshift, from the Hubble Deep Field.

LENNOX COWIE

Tanvir of Cambridge University; Matthew Colless at the Mount Stromlo Observatory; and Tom Broadhurst, now at the University of California, Berkeley—used the William Herschel Telescope in the Canary Islands and the HST to collect spectra and images of 200 faint galaxies. Their redshifts ranged from 0.1, which is nearby, to 1.2, a few billion years after the beginning, implying that at least some of these blue galaxies are at great distances. At about the same time, a Canadian-French team consisting of Simon Lilly and David Schade at the University of Toronto, David Crampton at Dominion Astrophysical Observatory, and Olivier LeFevre and François Hammer of the Meudon Observatory in France surveyed 600 galaxies with the Canada-France-Hawaii telescope in Hawaii and found much the same thing: redshifts ranging from 0.1 to 1.3.

Galactic adolescence. Both groups also found that these galaxies, like many adolescents, look peculiar. Says Ellis: "They're highly irregular objects, tadpoles and chains, that we don't see around today." His group called these irregulars compact blues. The Canadian-French team found the same thing, says Lilly; using HST they saw smallish galaxies with what he calls "rather more irregular, compact regions of bright blue emission." They called their galaxies blue nucleateds.

At an average redshift of 0.5, half the age of the universe, the irregular galaxies were the right age to be galactic adolescents. And their spectra show that they had adolescents' high metabolisms. The amount of ultraviolet radiation given off by newly forming stars in the irregular blues shows that they were forming stars at rates 10 times higher than those of local galaxies, just as expected of young galaxies. High star-formation rates can also explain the galaxies' irregular appearance, for stars are born in dense, bright patches. Even local galaxies that are prolific star formers look irregular when viewed in ultraviolet light. "If you look in the UV," says Lennox Cowie at the University of Hawaii, who has also spotted bright, distant irregulars among the faint blues using HST and the Keck (*Science*, 20 October 1995, p. 374), "things do look more beady and stringy."

But although distance and appearance seem to qualify the irregular blues as the adolescent form of today's spirals and ellipticals, the latest surveys imply that the picture isn't that neat. Observers are simply finding too many of them for there to be a one-to-one correspondence. In 1995, astronomers used HST to begin charting the universe's demographics by looking at patches of sky and simply counting and classifying faint galaxies. One such survey, HST's Medium Deep Survey, aimed HST at random small spots all over the sky for 1 to 2 hours per spot, each time picking up several hundred galaxies whose faintness suggested redshifts between 0.1 and 1.0. Among them, the density of irregulars was twice as high as the density of ordinary galaxies is today.

An even deeper look at the early universe, however, suggested what might be happening. Early this year, the Hubble Deep Field survey aimed HST at one patch of sky for an equivalent not of an hour or two but for 10 days. Robert Williams, the director of the Space Telescope Science Institute (STScI) in Baltimore and principal investigator of the survey, estimates that some of the 1500 galaxies this long exposure revealed have redshifts as high as 4.0 or 5.0, most of the way back to the big bang. "Looking at the Deep Field galaxies," says Lilly, "I have the feeling I'm looking at pretty well all there is."

Taking the long view. The Hubble Deep Field, which reveals galaxies most of the way back to the big bang.

STScI

When the British-Australian team classified and counted the galaxies in the Deep Field and compared the numbers with other surveys, they found that the fraction of irregulars increases at earlier times, from 10% close to home to 30% at a redshift of 0.5 to 40% at estimated redshifts of about 2.0 in the Deep Field. What's more, they saw spiral and elliptical galaxies even at the Deep Field's great distances, although the spirals, at least, were somewhat scarcer than they are today and were not the "beautiful and symmetrical spirals we're used to," says Glazebrook; rather, their disks were "irregular, knotty, and distorted" with "blue hot spots of star formation," suggesting that they had just formed.

To many of the galaxy hunters, the changing fraction of irregulars and the coexistence of galaxy types implies that not all the blue irregulars turned into today's galaxies. Only the largest and earliest of them might be ancestors of modern spirals. Some of the smaller irregulars may also have formed larger galaxies by merging, but others might have remained small. Because of their weaker gravity, these small galaxies would have been the last to form stars, well after larger galaxies like spirals and ellipticals had already taken shape; then they would have quickly run out of gas for making new stars and faded to invisibility. Peebles calls them galactic late bloomers—"the last gasp of field galaxy formation."

Infant galaxies. Carrying this history farther back in time means finding galaxies like those responsible for the quasar shadows and seeing what they actually look like. Observers had spotted a handful of faint splotches along the lines of sight to the quasars, but collecting enough light from them to determine redshifts and see if the splotches lie at the same distances as the shadows was difficult or impossible.

A few years ago, however, Charles Steidel and Kurt Adelberger at Caltech; Mauro Giavalisco at the Carnegie Observatories in Pasadena, California; Mark Dickinson at STScI; and Max Pettini at Cambridge exploited an efficient new technique to search for galaxies beyond a redshift of 3.0. Galaxies at such distances have a distinctive spectrum: The enormous volume of thin hydrogen gas through which their light passes on its way to the telescope completely blocks 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."

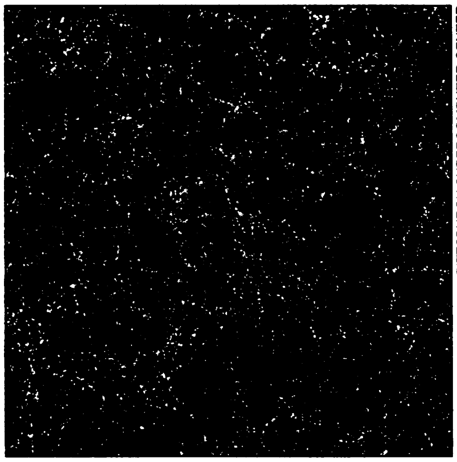
–Ann Finkbeiner

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 sur-