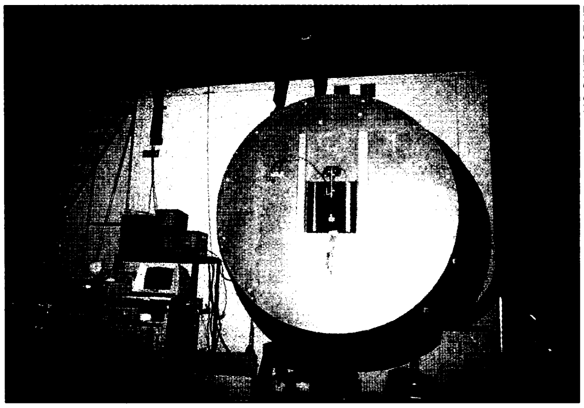
a deuterium abundance in an even more distant cloud almost 10 times lower than the earlier Keck measurement. If this value represents the true primordial abundance, then the scarcity of helium-3 in the present universe is no longer a puzzle. But the baryon-rich primordial universe it implies would have produced a higher ratio of primordial helium-4 to hydrogen than observers seem to find when they look at clouds in the nearby intergalactic medium.



UC SANTA CRUZ

Getting a line on deuterium. The high-resolution spectrograph at the Keck telescope and its builder, Steven Vogt.

There's no way to measure primordial helium-4 directly, for this isotope is continuously produced by stars. But astronomers can estimate how much of the helium in any given cloud is primordial and how much was generated in the stellar furnaces by taking into account the cloud's complement of heavier elements, which are only produced in stars. It's an uncertain process, but the results don't mesh comfortably with the Tytler group's measurements, says Bernard Pagel, a noted helium observer at NORDITA in Copenhagen, Denmark. "The Tytler result," he says, "stretches existing uncertainties in helium to their limits."

Such conflicts have led some researchers to question the standard theory of BBNS. When Walker, Naoya Hata, Robert Scherrer, Gary Steigman, and David Thomas at Ohio State, and Sidney Bludman and Paul Langacker at the University of Pennsylvania combined abundance measurements for all the light elements into a rigorous statistical analysis, they found the fewest discrepancies when they took numbers closer to the lower deuterium value as the correct ones. But even then, as implied by the title of the paper they published last November in *Physical Review Letters*—"Big Bang Nucleosynthesis in Crisis?"—they could see no easy way out of the contradictions without changing the standard picture of nucleosynthesis.

The team proposes that something might have slowed down the big bang during nucleosynthesis, allowing time for more neutrons to transmute into protons before the "freeze-out," thereby depleting the universe of neutrons and slightly reducing the amount of helium-4 that should emerge. If one of the three types of neutrinos, a particle commonly thought to be massless, actually does have substantial mass, it would have been moving more slowly in the early universe, taking just the right amount of oomph out of the expansion. The team chose the tau neutrino because it is the only kind whose properties remain uncertain enough to allow for such a large mass.

Unfortunately, most physicists believe that option strains credulity. "There is no experimental proof against a [very] massive tau," says David Caldwell of the University of California, Santa Barbara. "But I would bet a lot of money against it." There's only one thing for sure, says Karsten Jedamzik of Lawrence Livermore National Laboratory: "Whether the deuterium is high or low, you have problems."

Theorists also have to contend with the even more dizzying possibility that both measurements will turn out to be correct. If that's the case, says UCSD's George Fuller, "the first thing I would look at is whether [distant stars] could do it"—produce an uneven deuterium abundance by chewing up unexpectedly large amounts of deuterium in some places but not others in the early universe. If that didn't work, says Fuller, then "way down on the list," theorists would have to consider an inhomogeneous big bang, even though most calculations have shown that "nature seems to abhor an inhomogeneity."

Astronomers will have to take more readings from the deuterium baryometer before theorists will know which way to turn, says Tytler: "In order to show, for example, that there's a real variation, we would need some more high-precision measurements." The worst of cosmologists' problems will go away, says Tytler, "if we find the same [deuterium abundance] in different places," showing that one or the other of the present measurements is spurious. But even then, theorists don't expect to emerge unscathed from their closest brush with the big bang.

–James Glanz

SEEDS OF STRUCTURE

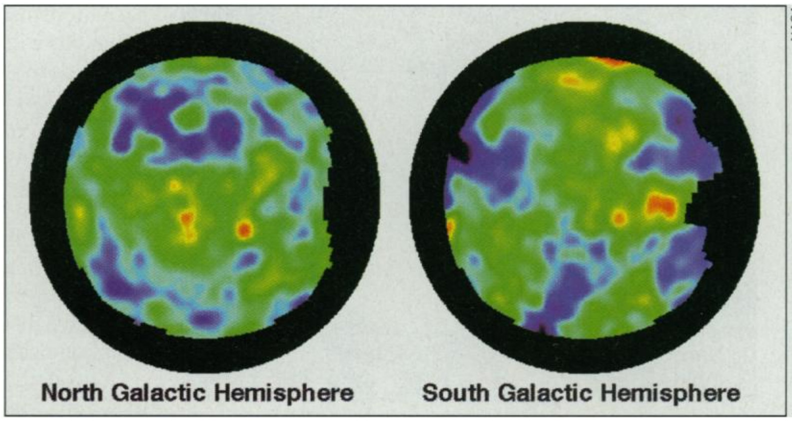
Microwave Wrinkles Promise Vital Statistics of the Cosmos

As a location to measure the background noise of the universe, Saskatoon, Canada, has been called the poor man's South Pole. Located in the midst of the Great Plains, 320 kilometers north of the Montana border, it is cold, dry, and flat. The result is a stable, uniformly cold air mass through which to view the cosmos, which happens to be a critical advantage for astrophysicists trying to measure variations of just one part in 100,000 in the temperature of a cold bath of microwaves known as the cosmic microwave background (CMB). Saskatoon's other advantage is simple, says Princeton University astrophysicist Lyman Page: It is the only place for hundreds of miles around that has "multiple hardware stores, a university, and an airport."

The right hardware and vantage point are what it takes these days to pursue questions that once belonged to priests and philosophers—questions about the origin, history, and future of the universe. Computer simulations of the CMB's formation in the early universe, together with experimental observations like those that Page and his colleagues are making in their Saskatoon experiment, called Bigplate, have persuaded astrophysicists and cosmologists that the CMB is about to yield some definitive answers. The CMB provides "a snapshot of the universe in its infancy," says University of Pennsylvania astrophysicist Paul Steinhardt. And the cosmic infancy, like human childhood, holds clues to much of what followed.

Since NASA's COBE satellite first revealed the fluctuations in the CMB in 1992, that promise has sparked what Steinhardt calls a "theoretical industry" dedicated to showing what could be teased out of better observations. Among the prizes are values of the Hubble constant, which is the rate at which the universe is expanding; of omega, the density of the universe, which determines whether or not the universe will expand forever; of omega baryon, the density of ordinary matter in the universe; and even of the cosmological constant, which is the energy density of the universe. "It is truly extraordinary," says Steinhardt, "the first time we have this window on the universe, a singular event in human history."

Getting a clear view through this window, however, will require observations more extensive than any of the dozen or so Earth-bound experiments now under way can deliver. But with the April announcement by NASA and the European Space Agency that, early in the next century, they will launch spacecraft to measure variations in the CMB with unprecedented accuracy, astrophysicists



Baby pictures. Temperature fluctuations in the microwave background, mapped by the COBE satellite. Finer scale maps are needed to answer cosmological questions.

now expect that they will soon nail down the vital statistics of the cosmos.

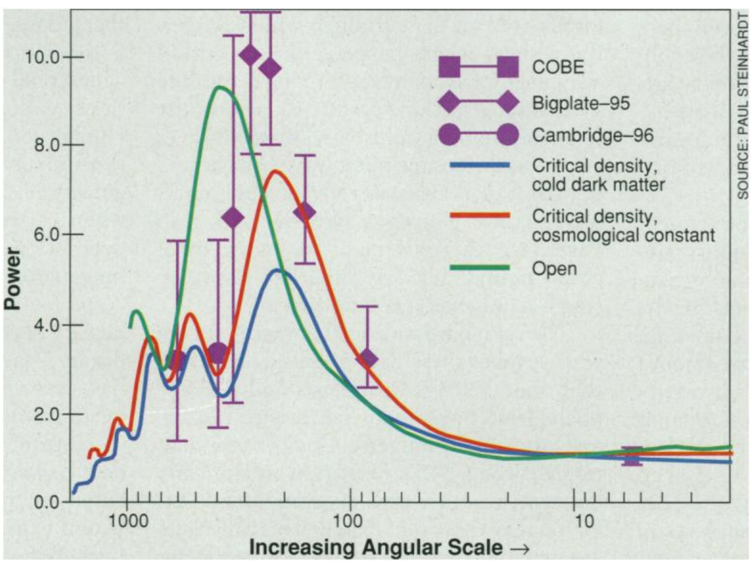
This optimism comes with one major caveat: that the current paradigm of the early universe, known as inflation, turns out to be the correct one. Inflation implies that the initial fluctuations in the newborn universe provided a simple starting pattern on which cosmic expansion, mass density, and other parameters left their marks before the CMB was formed. Other models of the early universe predict more complex beginnings that would make the CMB harder to interpret. And then, of course, there's always the possibility that cosmologists haven't a clue what the early universe was like, in which case the CMB fluctuations are likely to yield little information at all. Still, says University of California, Berkeley, astrophysicist Paul Richards, "if the data don't support [the current paradigms], then you've learned something very, very important, and you have a very good data set on which to test new paradigms."

The microwave radiation itself dates to a few hundred thousand years after the big bang, an epoch known as decoupling. Until then the universe was searing hot, ionized, and opaque: Photons scattered off the copious free electrons and went nowhere. "If you were to shine a flashlight into it," says Steinhardt, "the light couldn't travel very far before it was totally diffused by this scattering." As the universe cooled, the free nuclei began to capture electrons and form neutral atoms. With the electrons gone, the universe became transparent; "the radiation streams through it, and that's our microwave background radiation," says Steinhardt. "At that time it had a temperature of several thousand degrees. Now, due to the expansion of the universe, its effective temperature is just 3 degrees above absolute zero."

What interests astrophysicists is how much this temperature varies from point to point in the sky, known in the lingo as the anisotropy. The hot and cold patches reflect variations in the density of the universe at the time of decoupling—denser regions being cold and more tenuous regions being hot. And the key to the history and future of the cosmos is how these hot and cold patches are distributed across the sky, expressed in the form of a power spectrum, a plot of the average variation in the temperature as a function of angular scale.

Initial conditions. The information encoded in these variations depends on exactly how the initial seeds of structure were created in the first infinitesimal moment of the big bang. In one scenario, infinite stringlike fractures formed in the fabric of space-time, providing a framework around which galaxies and clusters of galaxies ultimately took shape. The string scenario is expected to result in a distinctive power spectrum, says Harvard University astrophysicist Arthur Kosowsky, with sharp discontinuities in the temperature at small angular scales. But gleaning cosmic parameters from the CMB in this scenario would be difficult.

The alternative scenario is the one that generates more optimism, because it provides an easily understood starting point. This is the inflationary universe model, which has been in vogue since the early 1980s. In it, Steinhardt explains, "a burst of incredible expansion" takes the universe from a "tiny patch of space" 10^{-30} centimeters across, considerably smaller than the nucleus of a hydrogen atom, and stretches it to cosmological size—all before the universe is 10^{-35} seconds old.



Mountainscapes. The microwave background's power spectrum, showing the angles on which its fluctuations are strongest, holds clues to the cosmic makeup. The graph shows three predicted spectra; measurements so far can't discriminate among them.

In this scenario, the seeds of structure formation are born even before the inflationary phase, when the universe was seething with quantum fluctuations on all possible scales, like waves of different sizes in some infinitesimal cosmic ocean. Inflation takes these quantum fluctuations and stretches them along with the rest of the universe. But it does not change their distribution, which remains in the form of Gaussian noise—a pattern of random variations that, like a fractal, looks the same on large scales as it does on small. It's the evolution of these fluctuations over the several hundred thousand years between inflation and decoupling that imprints them with so much information about the universe.

The key factor is known as the horizon of the universe, which is an ever-expanding sphere with a diameter equal to the speed of light times the age of the universe. Any density fluctuations on a scale smaller than that of the horizon are in causal contact: They are close enough to interact gravitationally. Those larger than the horizon are not, and so they could not interact before the microwave background was released. A fluctuation outside the horizon, says Kosowsky, "just sits there and doesn't do anything. It's called 'frozen out.' "

Thus fluctuations of an angular size larger than the horizon at the time of decoupling should have remained effectively random on all scales, just as they were in the early universe before inflation. That's what the Cosmic Background Explorer (COBE) satellite reported in April 1992. COBE, however, could only measure variations in the CMB at angular scales of 7 degrees on up—well outside the horizon and too coarse for cosmologists to regard this randomness as a decisive victory for inflation.

Inside the horizon, at angular scales of a degree or less, the universe should present a different story. Here theorists believe a push-me-pull-you effect, known as photon-baryon oscillations, was at work in the early universe. On the one hand, gravity tended to amplify the fluctuations in matter density. On the other, radiation pressure caused a repulsion, which tended to smooth out the fluctuations. The result, says Steinhardt, was "a series of oscillations: matter collapsing and then being pressed back." These oscillations—in effect, sound waves—left their mark on the CMB in a series of peaks, known as acoustic or Doppler peaks, rising out of the CMB power spectrum. "What you see," Steinhardt says, "is a series of mountains, beginning with one very prominent peak, and then the peaks begin to fall off and get smaller" at smaller angular scales.

The peaks result from waves that were at maximum compression or rarefaction at the time of decoupling, and hence produced the biggest fluctuations in energy density. The first of the peaks, at the largest angular scales, comes from the largest waves that could fit inside the horizon at that time. The peaks on smaller angular scales correspond to smaller waves, for which multiple cycles could fit inside the horizon. These peaks are lower because, after many oscillations, photons gradually diffused out of the fluctuations, smoothing them out—an effect that would have eroded smaller scale fluctuations more than larger ones.

Riches in those hills. It's in the heights and the positions of these various Doppler peaks that the cosmological parameters are hidden. Take the density of the universe, known as omega, which is encoded in the position of the first and biggest Doppler peak. Because cosmologists know how big the horizon must have been when the microwave background formed—they multiply the age of the universe at that time by the speed of light—they can calculate the wavelength of the fluctuations responsible for the first peak.

The relation of that dimension to the angular scale at which it shows up on the sky today reveals omega, because the mass density of the universe affects the shape of space and hence how photons travel through it. It's a kind of cosmic optics: "The only effect that can alter the apparent size on the sky today is the shape of the universe," says Kosowsky. If we live in a universe that is at what astrophysicists refer to as critical density, just perched between recollapsing and expanding forever, then the universe is literally flat, and photons follow a straight line. In that case, says Kosowsky, the first peak turns out to fall at an angular scale of roughly 1 degree. If the universe is open, however, and is expanding forever, then the photons will follow hyperbolic paths, shrinking the peak's apparent scale.

"If omega equals 0.2—a number that is popular with cosmologists because you can construct a universe like that without having to add much dark matter—the peak would be shifted from 1 degree to roughly a half degree," says Kosowsky. "And that turns out to be a really big difference when you are actually measuring things. A piece of cake to pick out."

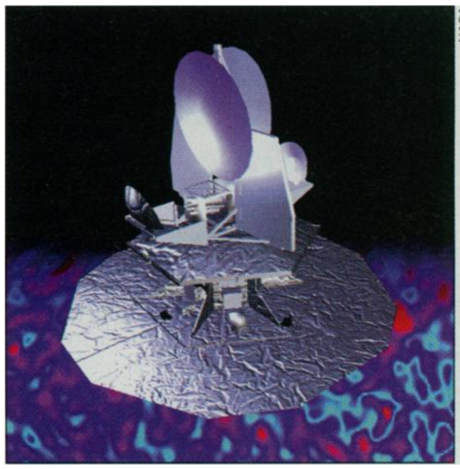
After omega, say cosmologists, it takes a little more work to pick out cosmological parameters from the power spectrum. For instance, the spacing between the first peak and the second peak depends on how much of the universe is made of ordinary matter, a quantity known as omega baryon. Cosmologists have another way of predicting that number, based on the universe's complement of helium and deuterium—elements forged in the big bang in amounts that depend on the density of ordinary matter (see p. 1429). But the CMB power spectrum should give an independent measurement, says David Spergel of Princeton.

It may also yield an independent check on the Hubble constant. Astronomers are struggling to distill this measure—crucial to knowing both the size and present age of the universe—from observations of distant stars and galaxies (*Science*, 24 November 1995, p. 1295). But it can also be extracted from the CMB by identifying the time when the universe made its transition from being radiation dominated, which means the bulk of its mass-energy was in the form of energetic photons and particles moving near the speed of light, to being dominated by slower moving matter, says Spergel. As long as the universe was radiation dominated, gravity could not amplify density fluctuations. As soon as the universe cooled below some critical temperature—"somewhere between 4000 degrees and 40,000 degrees," says Spergel—those fluctuations could start evolving and growing. "Since we're looking at the fluctuations, we can see whether they're growing or not from what the spectrum looks like," he says.

In particular, the shift from radiation dominance to matter dominance would show up in the amplitude of the fluctuations on scales between 1 and 2 degrees. The fluctuations should be about 5% larger if the radiation-matter transition took place just before decoupling than if it came earlier, says Spergel. The time of the transition in turn depends on the ratio of mass to photons in the universe—the higher that ratio the earlier the shift to matter dominance—and on how fast the universe was expanding. "Since we can measure omega from the location of the first peak," says Spergel, "that then gives us the Hubble constant."

MAPing microwaves. All that is needed is more experimental data, which is "the hard part," as Spergel puts it. There are currently some dozen experiments measuring the microwave anisotropy, from the north and south poles and locations in between ranging from Saskatoon to Cambridge, England. These experiments are measuring at angular scales of half a degree up to tens of degrees, but each tends to measure only at a single angular scale or looks at only a small patch of sky. As a result, "the errors are still big," says Spergel. But the results are encouraging nonetheless. "The fact that different experiments measuring different regions of the sky get comparable fluctuation amplitudes and that experiments ... on the same regions of the sky get similar results suggests there is no sign of trouble."

The latest experimental results—from the Princeton Bigplate experiment; MAX, a balloon experiment run out of Berkeley and the University of California, Santa Barbara; and MSAM, a balloon experiment run out of the University of Chicago and NASA Goddard Space Flight Center—even show the first signs of the peak at 1 degree. The apparent emergence of the peak has dispelled one worry: a possible reionization of the early universe from any number of high-energy events that could have occurred when the universe was a few tens of millions of years old. Electrons freed in these processes would have interacted with the CMB's photons and wiped out all the information it preserved. "Instead of seeing the peak," says Steinhardt, "we'd see the signal disappear at this 1-degree scale. The fact we're seeing a rise means there was no such dramatic event and the information is there to be had."


NASA

Cosmic cartographer. MAP spacecraft will chart details of the microwave background.

The basic outline of this information should come from the next generation of experiments, either long-duration balloon flights or ground-based experiments. These will look at large swaths of the sky and take data on all angular scales. Balloons launched from Antarctica, for example, will stay aloft for a week at a time in the vortex of air that 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

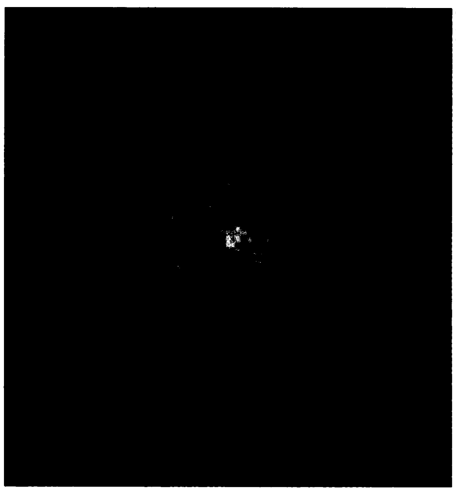
From Snapshots of Distant Galaxies, a History Emerges

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