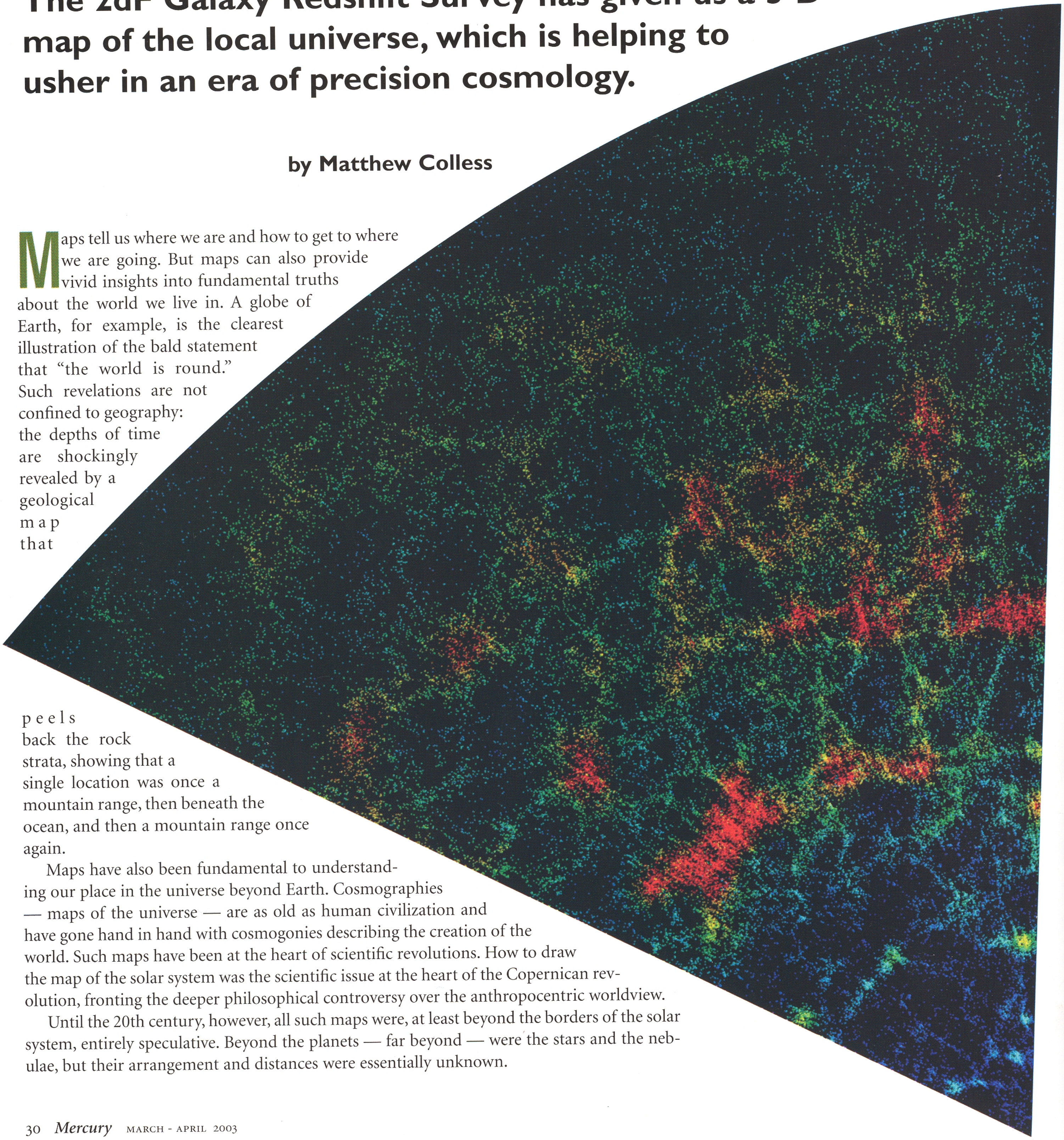
# THE GREAT COSMIC MAP

## The 2dF Galaxy Redshift Survey has given us a 3-D map of the local universe, which is helping to usher in an era of precision cosmology.

**by Matthew Colless**



Maps tell us where we are and how to get to where we are going. But maps can also provide vivid insights into fundamental truths about the world we live in. A globe of Earth, for example, is the clearest illustration of the bald statement that "the world is round." Such revelations are not confined to geography: the depths of time are shockingly revealed by a geological map that peels back the rock strata, showing that a single location was once a mountain range, then beneath the ocean, and then a mountain range once again.

Maps have also been fundamental to understanding our place in the universe beyond Earth. Cosmographies — maps of the universe — are as old as human civilization and have gone hand in hand with cosmogonies describing the creation of the world. Such maps have been at the heart of scientific revolutions. How to draw the map of the solar system was the scientific issue at the heart of the Copernican revolution, fronting the deeper philosophical controversy over the anthropocentric worldview.

Until the 20th century, however, all such maps were, at least beyond the borders of the solar system, entirely speculative. Beyond the planets — far beyond — were the stars and the nebulae, but their arrangement and distances were essentially unknown.

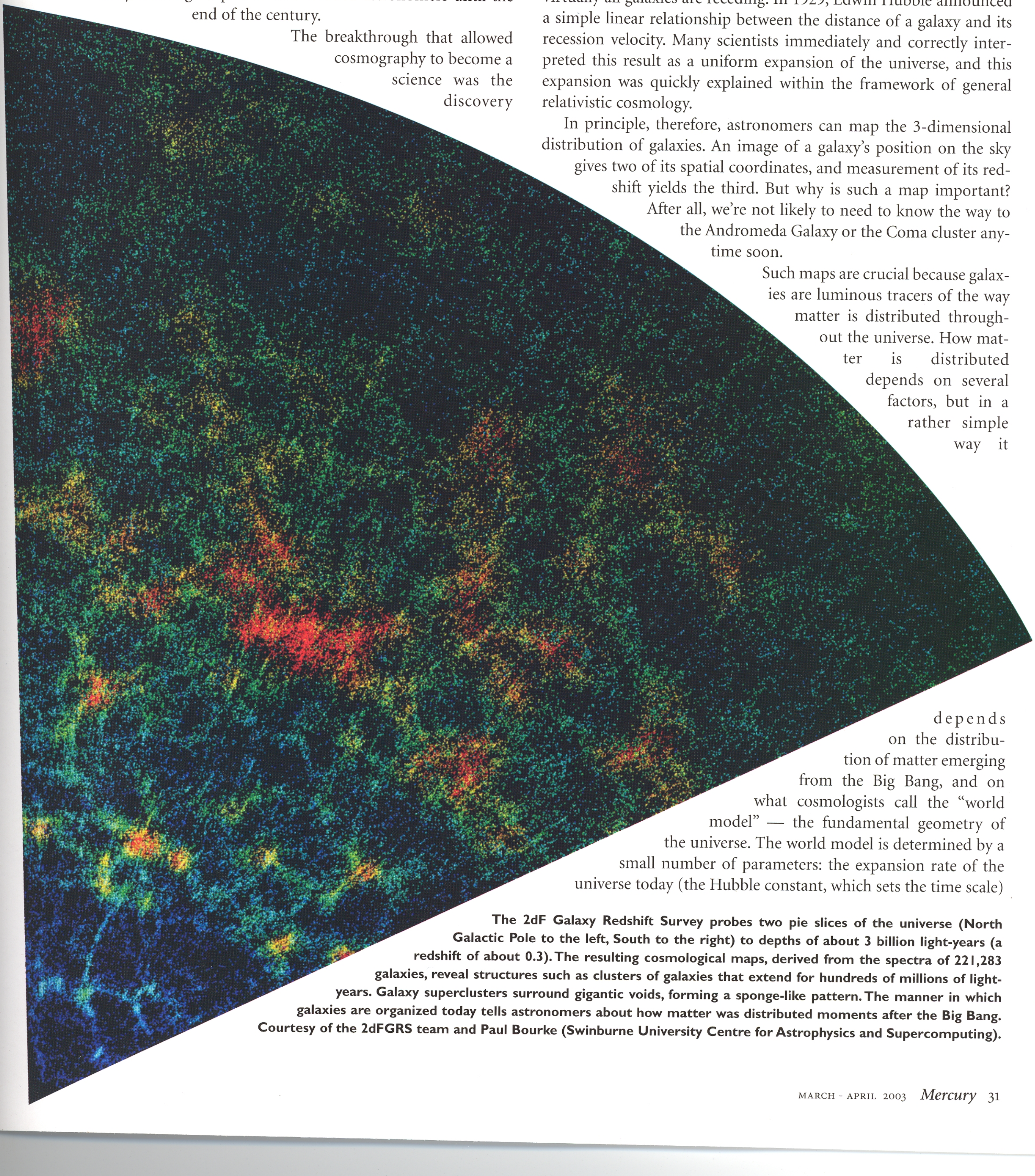
## Galaxies and Cosmology

The advances of 20th-century astronomy showed that stars belong to a single great spiral galaxy and that spiral nebulae were similar stellar structures at vast distances. On the universe's largest scales, galaxies appeared to be the natural units into which matter is organized. A range of painstaking observations in the early 20th century showed that the nearest of these other galaxies are millions of light-years away, although a precise scale eluded astronomers until the end of the century.

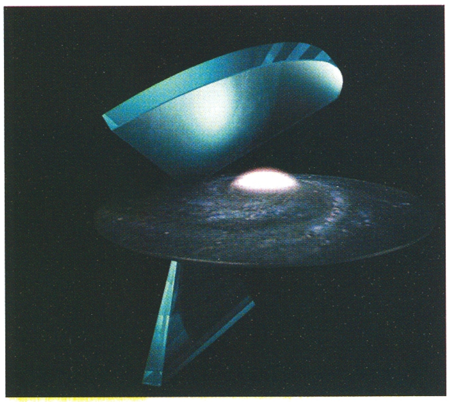
The breakthrough that allowed cosmography to become a science was the discovery of a straightforward means of measuring the relative distances to galaxies. Astronomers measured the spectra of many galaxies and found that in almost all cases the atomic features in their spectra are slightly shifted to longer, redder wavelengths compared with their laboratory values. Astronomers interpreted this effect as a Doppler shift resulting from the motion of these galaxies relative to our own, with the preponderance of redshifts over blueshifts implying that virtually all galaxies are receding. In 1929, Edwin Hubble announced a simple linear relationship between the distance of a galaxy and its recession velocity. Many scientists immediately and correctly interpreted this result as a uniform expansion of the universe, and this expansion was quickly explained within the framework of general relativistic cosmology.

In principle, therefore, astronomers can map the 3-dimensional distribution of galaxies. An image of a galaxy's position on the sky gives two of its spatial coordinates, and measurement of its redshift yields the third. But why is such a map important? After all, we're not likely to need to know the way to the Andromeda Galaxy or the Coma cluster anytime soon.

Such maps are crucial because galaxies are luminous tracers of the way matter is distributed throughout the universe. How matter is distributed depends on several factors, but in a rather simple way it depends on the distribution of matter emerging from the Big Bang, and on what cosmologists call the "world model" — the fundamental geometry of the universe. The world model is determined by a small number of parameters: the expansion rate of the universe today (the Hubble constant, which sets the time scale)



**The 2dF Galaxy Redshift Survey probes two pie slices of the universe (North Galactic Pole to the left, South to the right) to depths of about 3 billion light-years (a redshift of about 0.3). The resulting cosmological maps, derived from the spectra of 221,283 galaxies, reveal structures such as clusters of galaxies that extend for hundreds of millions of light-years. Galaxy superclusters surround gigantic voids, forming a sponge-like pattern. The manner in which galaxies are organized today tells astronomers about how matter was distributed moments after the Big Bang. Courtesy of the 2dFGRS team and Paul Bourke (Swinburne University Centre for Astrophysics and Supercomputing).**



**The 2dF survey probed two slices of the universe, aimed in the directions of the North and South Galactic Poles, respectively. This illustration shows the directions of these slices with respect to the Milky Way Galaxy; the actual slices extend to much greater distances than those shown here. Courtesy of Robert Smith (Liverpool John Moore University).**

and the energy densities corresponding to the various constituents making up our amazing universe. These energy densities include various forms of matter, radiation, and, possibly, the energy of "empty" space (Einstein's cosmological constant).

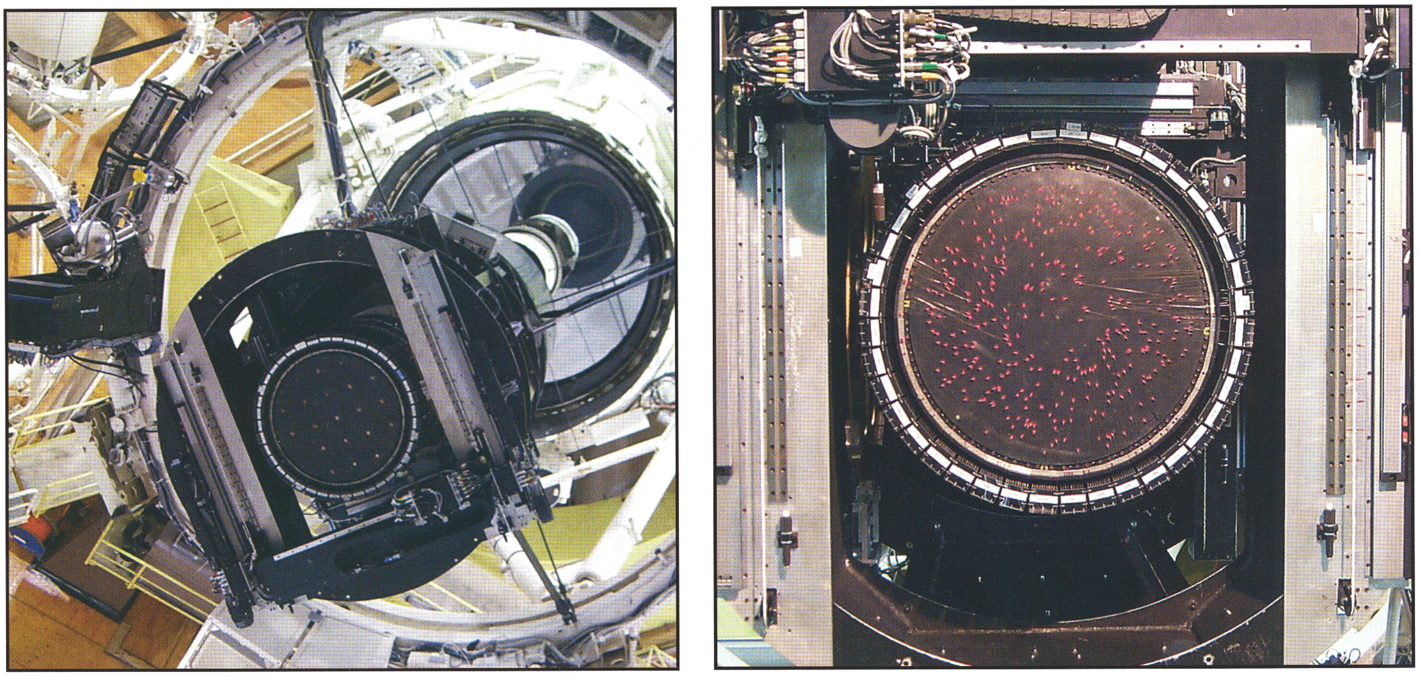
Given the world model and the initial distribution of matter, we can calculate the evolution of the distribution of matter at later epochs by applying Newton's laws of gravity. Using this method, we can test whether a particular cosmological model is correct by comparing its prediction for where the matter is today with the observed 3-dimensional distribution of galaxies. In other words, we can measure cosmological parameters directly from the present-day distribution of galaxies. This research program offers the possibility of determining the world model by combining straightforward observations (positions and redshifts) with well-understood physics (gravity).

## Mass-Production Redshift Surveys

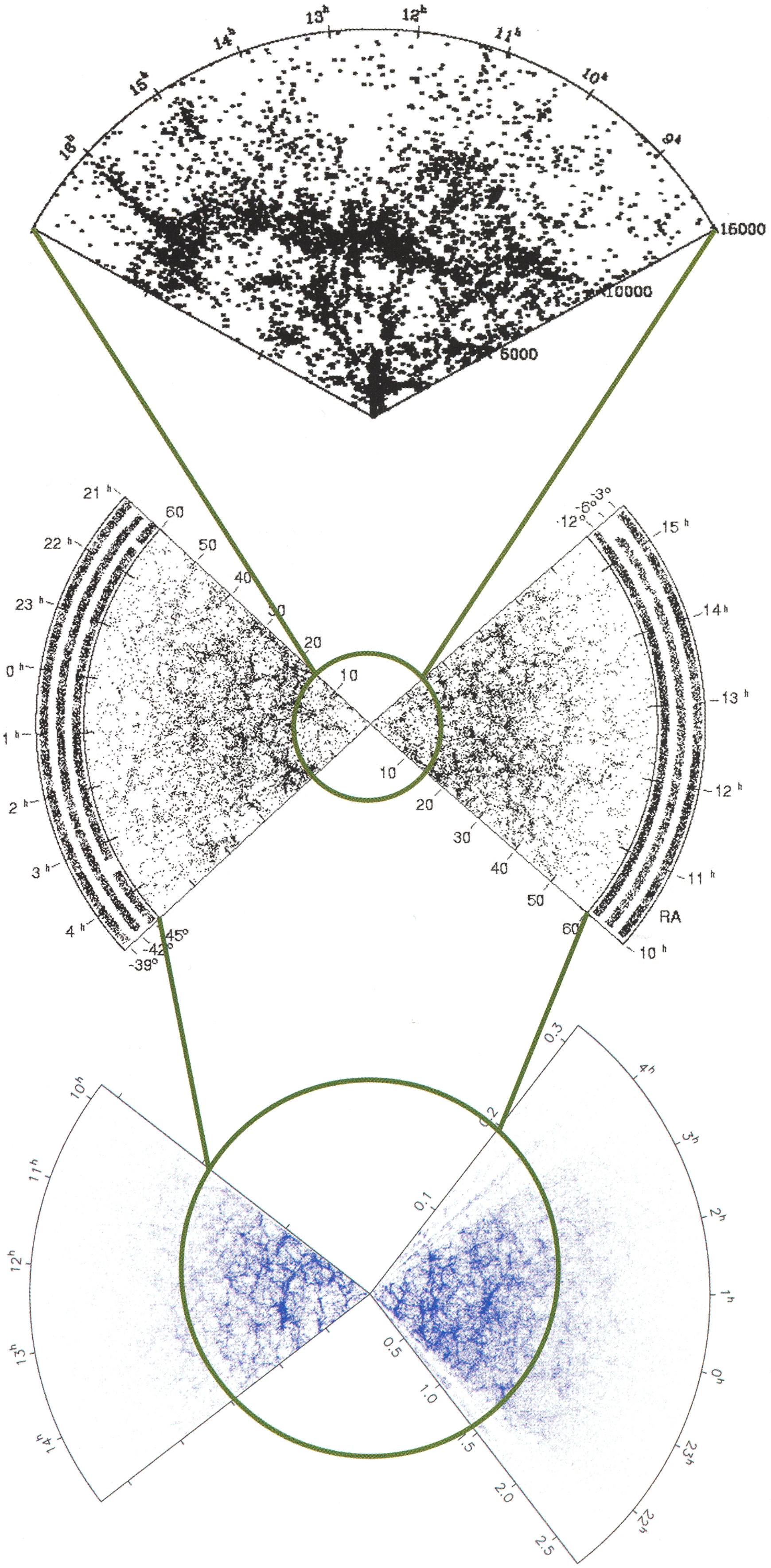
During the 1980s a group at the Harvard-Smithsonian Center for Astrophysics (CfA), led by Margaret Geller and John Huchra, pioneered the first large galaxy redshift surveys. The CfA maps of the nearby universe became inspirational icons in cosmology, because they made plain for the first time the size and complexity of the large-scale structures in the distribution of galaxies. These observations fueled a rapid development of both the physical theory underlying the formation of large-scale structure and the mathematical and statistical tools for its description and analysis.

But the CfA redshift survey and its successors, such as the Las Campanas Redshift Survey and a redshift survey based on the catalog of sources produced by the Infrared Astronomy Satellite (IRAS), had significant limitations. The CfA survey, for example, covered only a narrow slice of the sky out to modest distances of about 500 million light-years and was dominated by a single filamentary structure (dubbed the Great Wall) that linked the most massive galaxy clusters in the volume. This is not a sufficiently large volume to represent a fair sample of the universe. The IRAS redshift survey covered a volume of about a billion cubic light-years, but it sampled this volume so sparsely, around 1 galaxy every 100,000 cubic light-years, that the structures in this volume are not well defined. Simulations show that any galaxy redshift survey aiming to measure cosmological parameters with 10% precision needs to contain more than 100,000 galaxies and cover more than a billion cubic light-years. How could such a massive redshift survey be accomplished?

The CfA and IRAS surveys each covered around 15,000 galaxies, measuring redshifts one at a time. This ponderous approach clearly would not suffice if the survey size had to be increased by an order of magnitude. A mass-production method was clearly needed to achieve this goal. Fortunately, over the previous decade astronomers had developed various techniques for multi-object spectroscopy, and one of these, fiber-optic spectroscopy, proved to be ideally suited to large redshift surveys. Using this technique, we can exploit the full focal plane of the telescope by placing optical fibers at the position of each object of interest and then bringing these fibers together in a spectrograph that measures the spectra for all the targeted



**Left: The 2dF instrument is connected to the prime focus of the Anglo-Australian Telescope. Right: The round plate's red dots mark the location where a robot positions optical fibers to record the spectra of several hundred individual galaxies simultaneously. Courtesy of the 2dFGRS team.**



**The CfA Redshift Survey (top) of the 1980s broke new ground by revealing galaxy superclusters and gigantic voids out to distances of about 600 million light-years (a redshift of about 0.06). The Las Campanas Redshift Survey of the 1990s (center) extended astronomers' reach to nearly 2 billion light-years. But because these earlier redshift surveys had smaller fields of view and could observe fewer galaxies simultaneously, they covered only a tiny volume of space compared with that covered by the 2dF survey (bottom). CfA redshift map courtesy of John Huchra and Margaret Geller, Smithsonian Astrophysical Observatory. Las Campanas map courtesy of Stephen Shectman (OCIW) et al., *Ap.J.* 470, 172, 1996. 2dF redshift map courtesy of the 2dFGRS team.**

objects simultaneously. The Las Campanas survey adopted this approach, using a 112-fiber spectrograph to measure redshifts for 25,000 galaxies. But further developments were required for an order-of-magnitude increase in survey size.

## The 2dF Galaxy Redshift Survey

The U.K. Large Telescope Panel planted the seed for the 2dF Galaxy Redshift Survey in the late 1980s when it assigned high priority to converting existing telescopes to wide-field science, especially multi-object spectroscopy. The Anglo-Australian Observatory (AAO) 3.9-meter telescope was particularly well suited for such a conversion. In the late 1980s telescope designers Roderick Willstrop and Charles Wynne had shown that with suitable correction optics, the AAT could be adapted to image a 2° diameter field of view at its prime focus. Moreover, the AAO had been among the first to develop multi-fiber spectroscopy and had already built two multi-fiber spectrographs.

Under the leadership of Russell Cannon and Keith Taylor, the AAO seized the opportunity to exploit this fortuitous convergence of capabilities and scientific need and designed a new wide-field, multi-object spectrograph: the Two-degree Field facility (2dF). The essential feature of 2dF was that it could measure spectra of up to 400 galaxies simultaneously over a 2° region of sky (16 times the area of the full Moon). Massive additional lenses were added to the AAT to produce high-quality images over this large field of view. But the key was to use a high-precision robot to position optical fibers over the images of up to 400 galaxies. The optical fibers were then brought together in the 2dF spectrographs so that the galaxies' spectra could all be measured at once. In fact, 2dF was equipped with two sets of 400 fibers, so that while one set of fibers observes the sky, the robot could configure the second set. At the end of the observation, the two sets of fibers were swapped, allowing observations to be carried out almost continuously, so that 2dF could measure a whopping 400 galaxy redshifts every hour.

A massive redshift survey aimed at measuring fundamental cosmological parameters was one of the scientific drivers for the 2dF facility from its conception. The founding members of the survey team developed this idea into a detailed, concrete proposal during 1993 and 1994. Their proposal envisaged a redshift survey of 250,000 galaxies over about 5% of the sky with a mean redshift of about 0.1, corresponding to a depth of more than a billion light-years.

The galaxies in the sample were chosen to have blue magnitudes brighter than 19.5, because at this limit the number of galaxies over a 2° field was well matched to the number of fibers in 2dF. The plan was to survey two long strips of sky, one centered on the South Galactic Pole (SGP) and the other toward the North Galactic Pole (NGP). In addition, 100 survey fields were scattered over a much larger region around the SGP strip in order to probe sparsely the galaxy distribution on the largest possible scales. Choosing regions at the galactic poles avoids confusion with stars and much of the absorption caused by dust lying in the galactic plane.

We took the first spectra with 2dF in mid-1996, and scheduled observations with full functionality began in September 1997. The first major observing run for the 2dF Galaxy Redshift Survey (2dFGRS) occurred in October 1997. Progress with the survey was slow to begin with, mainly because of problems in getting the fiber positioner operating at full speed. It took nearly 2 years to gather the first 50,000 redshifts, but the 100,000th redshift was measured just 1 year later, in mid-2000. The first 100,000 redshifts and spectra were released publicly in June 2001, and the 200,000-redshift mark was achieved toward the end of 2001.

After 5 years and 272 nights on the AAT, observations for the 2dFGRS were finally completed on April 11, 2002. In sum, the survey measured redshifts for 221,283 galaxies. Many large structures — clusters, filaments, and voids — are apparent in the resulting maps (see pages 30 and 31), which are the first truly representative pictures of the matter distribution in the local universe.

## Cosmological Results

The first results to emerge from the survey are measurements of fundamental cosmological parameters based on the structure in the distribution of galaxies. The 2dFGRS map unveils a complex web of structures: large, almost empty voids surrounded by relatively thin sheets, intersecting in long filaments that in turn meet at dense nodes — galaxy clusters. The map provides both a precise measurement of the mean density of galaxies and the sizes of the density fluctuations on scales ranging from a million to a billion light-years. These structures are more clearly visible at small scales than large scales, reflecting the crucial fact that the universe is nearly homogeneous on the largest scales.

Our first step was to statistically characterize the large-scale structure so we could compare it with the theoretical predictions. In most cosmological models, the galaxy distribution is fully described, in statistical terms, by just two quantities: the mean density of matter and the way fluctuations in matter density vary with scale.

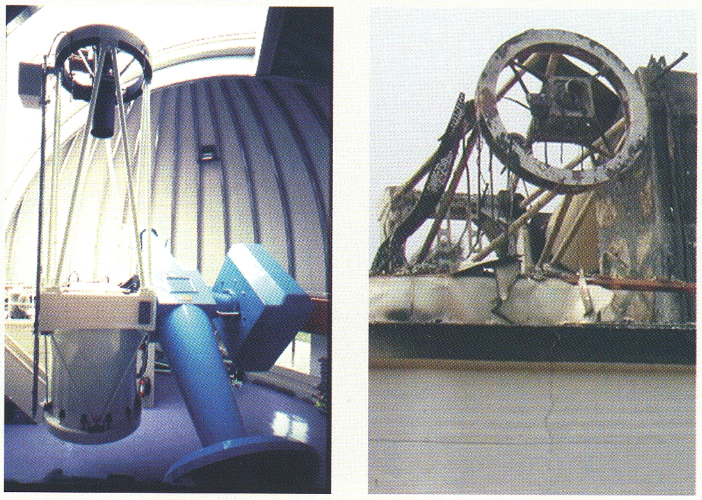
As part of this effort we detected a difference in structures seen along our line of sight compared with those across our line of sight. This difference, long predicted but not seen clearly in previous surveys, results from the fact that redshift measures not only the distance to a galaxy, but also the galaxy's motion along the line of sight due to the gravitational pull of surrounding galaxies. Large-scale structure has no preferred orientation, so this random galactic motion makes structures in the redshift map appear to be either stretched or squashed along our line of sight. In the 2dFGRS we observed a tendency for the larger structures to appear compressed along the line of sight because galaxies are on average falling toward one another under their mutual gravitational attraction. This result clearly demonstrates that structures in the galaxy distribution formed over billions of years by gravity amplifying tiny density fluctuations emerging from the Big Bang.

The map reveals larger variations in mass density at smaller and smaller size scales. But some size scales are minutely enhanced while others are minutely suppressed. This modulation is the distinctive signature of interactions between baryonic matter (the kind of matter that makes up stars, planets, and people) and photons during the universe's early history. During this epoch, high-density regions collapsed until radiation pressure exceeded the gravitational force, at which point they expanded until gravity again dominated. These oscillations in matter density ceased about 300,000 years after the Big Bang, when the universe had cooled. At this

**The 2dF Galaxy Redshift Survey was conducted on the 3.9-meter Anglo-Australian Telescope, whose dome is shown above. Copyright Anglo-Australian Telescope Board. Photograph by David Malin.**

## Mount Stromlo Observatory Ravaged by Fire

As I was editing this article on the 2dF Galaxy Redshift Survey, I was saddened to hear the news that the bushfires raging around Canberra, Australia killed 4 people and almost totally destroyed the historic Mount Stromlo Observatory. The observatory was home to five telescopes, including 50- and 74-inch reflectors, and a leading instrument workshop that was putting the finishing touches on a spectrograph for the 8.1-meter Gemini North Telescope in Hawai'i. "The loss of Mount Stromlo is a devastating blow to Australian research and in particular to the 60 staff and 20 students who made it their workplace," said Ian Chubb, vice chancellor of the Australian National University, which operates the observatory. The ASP officers, Board of Directors, and staff are thankful that no observatory personnel or students were killed or injured by the fire, and we applaud the university's commitment to rebuild the observatory. Still, we send our deepest condolences to the people who lost loved ones, and to our friends and colleagues in the Australian astronomical community. — *Robert Naeye*



**Left: The Mount Stromlo Observatory, near Canberra, Australia, was home to this 50-inch reflector. Right: This photo shows the remains of the 50-inch reflector after bushfires destroyed most of the observatory on January 18, 2003. The telescope was originally built in Dublin, Ireland in 1856. It was the telescope used in the MACHO survey, which found the first dark matter gravitational lensing events in the galactic halo. Left photo courtesy of Bob Cooper (ANU). Right photo courtesy of Matthew Colless.**

time, the typical matter density on a particular scale depended on whether the oscillations on that scale were causing matter to compress or become more rarified. Gravity has amplified these early mass fluctuations over the past 14 billion years, but the relative densities of this primordial era are still echoed today in the distribution of matter. Astronomers had previously seen this effect in the cosmic microwave background (CMB) but not in the distribution of galaxies.

Another major achievement of the 2dFGRS was the first direct measurement of how the galaxy distribution differs from the overall matter distribution, which is dominated by the mysterious dark matter. Although galaxies appear to exist where the density of mass is highest, these peaks may give us a biased picture of where most of the universe's mass is located. Moreover, different types of galaxies have different distributions, with spiral galaxies preferring lower-density environments and ellipticals preferring high-density groups and clusters, so clearly they cannot all reflect the distribution of matter in the same way

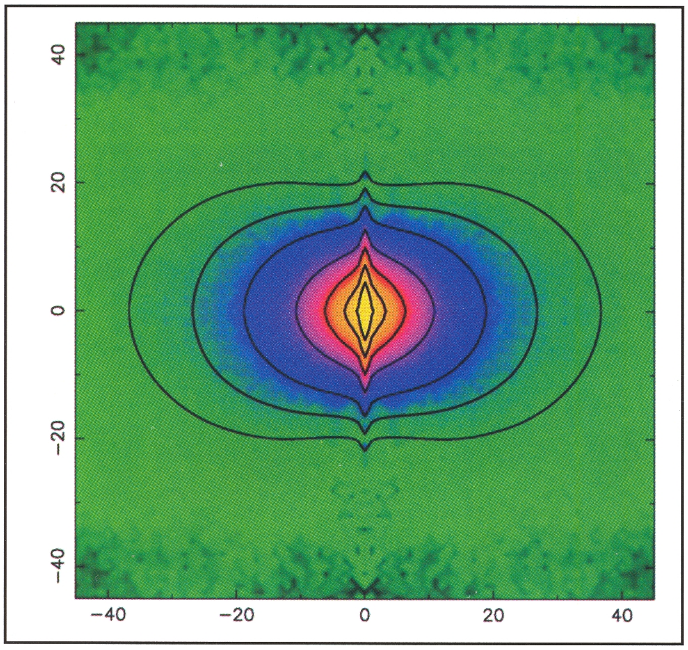
One way to measure this bias is to compare the density fluctuations of galaxies with those of the mass. Because most of the mass consists of dark matter, we cannot see the mass distribution directly in the present-day universe. But on large scales, we can compute it reliably from the mass distribution at very early times as revealed by the CMB. Comparing the observed fluctuations in the galaxies and the predicted fluctuations in the matter computed from the CMB therefore gives one a measure of the bias.

A second method is to look at smaller scales, where the gravitational amplification of structure begins to form complex structures like clusters of galaxies. The precise shapes of these structures depend on the bias, so that by measuring the detailed arrangement of galaxies in and around clusters we can obtain a measurement of the bias from the redshift survey alone. These two independent methods for measuring the bias from the 2dFGRS yield entirely consistent results and show that galaxies with optical luminosities similar to that of the Milky Way are nearly perfect tracers of the overall mass distribution, having the same density fluctuations as the dark matter. These analyses also provided valuable constraints on models of galaxy formation and evolution.

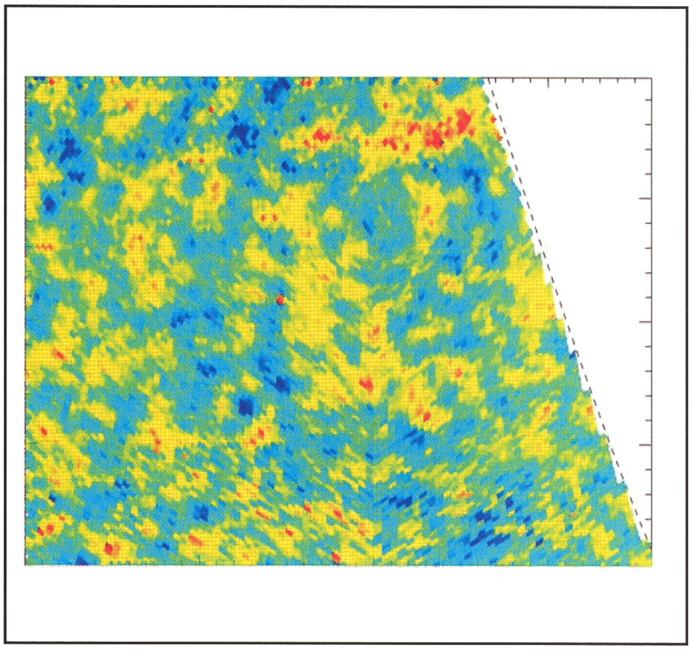
### Fundamental Parameters

Combining all of these results allows us to determine several fundamental cosmological parameters. We can determine the mean mass density of all forms of matter in the universe by determining how density fluctuations in galaxies vary as a function of scale, and, after making a correction for the bias, from the form of the redshift space distortions resulting from the galaxies' random motions. The best estimate of the mass density is 26 ± 5% of the critical mass density needed for a geometrically flat universe predicted by inflationary theory. Further comparison of the density fluctuation of galaxies with temperature fluctuations in the CMB shows that baryons have only 4.4 ± 1.6% of the total mass needed for a flat universe. In other words, the 2dFGRS confirms that there is about five times as much dark matter in the universe as baryons.

The density fluctuation of galaxies also gives an upper limit for the contribution to the total mass density of neutrinos. Because neutrinos are extremely light particles, they travel at near light speed. Consequently, they rapidly diffused out of any small existing mass concentrations in the very early



**The 2dFGRS detected the compression of structures in the galaxy distribution along our line of sight, which results from galaxies falling toward one another because of their mutual gravitational attraction. This compression shows up as a squashing of the contours in redshift (vertical axis) at large separations on the sky. The amount of compression is directly related to the density of matter in the universe. Courtesy of the 2dFGRS team.**



**The BOOMERanG balloon experiment revealed small-scale temperature variations in the cosmic microwave background. By comparing the sizes of these fluctuations with the distribution of visible mass (galaxies) as seen by 2dFGRS, astronomers determined that the distribution of visible mass is an excellent tracer for the overall distribution of mass (which consists mostly of dark matter) in the universe. Courtesy of the BOOMERanG Collaboration.**

universe, decreasing the typical size of mass fluctuations on small scales. This effect is larger if neutrinos contribute a larger fraction of the overall mass density. By measuring the fluctuations on small scales, the 2dFGRS was able to show conclusively that neutrinos contribute no more than 13% of the mass needed for a flat universe. The sum total mass of all 3 neutrino types is less than 3-millionths the mass of the electron.

Finally, a detailed comparison of the galaxy distribution and the CMB yields estimates for a Hubble constant of 72 ± 7 kilometers per second per megaparsec, and a cosmological constant that is 70 ± 10% of the mass-energy needed for a flat universe. Even though these measurements were derived independently, they are in excellent agreement with the best previous estimates, which for the Hubble constant come from the Hubble Space Telescope Key Project and for the cosmological constant come from observations of distant Type Ia supernovae. They confirm that some unknown form of "dark energy" is the dominant constituent of the universe and is causing the expansion of the universe to accelerate.

The cosmological parameters measured from the 2dFGRS have made a significant contribution to shaping the current consensus on the fundamental properties of the universe. This consensus has emerged over the past few years from a range of independent observations, including the measurements of slight temperature variations in the CMB, the distances to high-redshift supernovae, and Big Bang nucleosynthesis. But the power of galaxy redshift surveys as probes of cosmic structure can be taken much farther. New surveys are extending such work in a variety of ways. The Sloan Digital Sky Survey will look at nearly a million galaxies over a quarter of the sky. The 6dF Galaxy Survey will map the very nearby volume of the universe, measuring galaxy positions and velocities. Surveys of the very distant universe are beginning to probe the formation of galaxies and the evolution of the universe. Look how far cosmography has come, and how far it can still take us! **m**

---

*MATTHEW COLLESS (www.mso.anu.edu.au/colless) is an astronomer at the Australian National University and coleader of the 2dF Galaxy Redshift Survey team. As well as continuing to analyze the results from the 2dFGRS, he is also leading the new 6dF Galaxy Survey, which will further constrain cosmological models. The website for the 2dFGRS is www.mso.anu.edu.au/2dFGRS.*

## The 6dF Galaxy Survey

The 6dF Galaxy Survey (www.mso.anu.edu.au/6dFGS) is mapping galaxies in the nearby universe over the whole Southern Hemisphere, using the Anglo-Australian Observatory's Schmidt Telescope and the 6dF fiber spectrograph. The target list of galaxies is provided by the 2MASS survey. Redshifts will be measured for about 150,000 galaxies, but the survey will also measure random motions for about 15,000 of these galaxies. By mapping both the galaxies' positions and these random motions, the 6dF Galaxy Survey will derive new and more precise measurements of the mass distribution in the universe and the formation of structure. — *M. C.*