at which the conductance rises from zero and then settles to its constant value. The self-consistent solution of Gygi and Schlüter shows that not just the density of states but also the gap function may show fine structure; that is, it might have ripples on length scales smaller than the coherence length.

Sixfold symmetry

There are three further effects that theories must take into account: interaction between flux lines or the possibility of tunneling between states bound to neighboring vortices; the role of material impurities and imperfections; and the role of the symmetry of the underlying $NbSe_2$ crystal structure. Gygi and Schlüter and, independently, Klein have examined the modifications in the tunneling conductance due to interaction between flux lines. Klein also reports that the height and width of the zero-bias peak depends on parameters measuring impurities and imperfections in the materials.[5]

The picture on the cover of this issue shows the conductance around a vortex core at zero bias voltage. In the color code used, the conductance (or the density of states) is larger than the value in the normal state of 2H-$NbSe_2$ in white, yellow and red regions, and smaller than the normal-state value in green and blue regions. Similar plots of data at fixed bias voltages show that the size of the core region increases with increasing magnitude of the bias voltage, indicating that the STM probes wavefunctions that are increasingly spread out from the center. The plots also show sixfold symmetry in the angular dependence of the density of states around a vortex, which arises from the hexagonal symmetry of the $NbSe_2$ lattice. The six-fold pattern undergoes a twist at some value of the bias voltage.[4] Schlüter told us that the energy spectrum, when regarded as a function of, or as having a "band structure" in, angular momentum, splits into two branches (or sub-bands) when the Bogoliubov–de Gennes equations are coupled to the underlying lattice. The branch of the spectrum that the STM tip probes changes at some value of the bias voltage, causing the twist because the subbands have different symmetry orientations.[6]

Earlier attempts to use the STM to study the density of states in type II superconductors probably suffered from poor surface quality, Hess conjectures. —Anil Khurana

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GIGANTIC STRUCTURES CHALLENGE STANDARD VIEW OF COSMIC EVOLUTION

These are exciting times for cosmologists. The "standard cosmological model" that purports to describe the evolution of the universe is being tested at both ends by spectacular astronomical observations. On the one hand are the recently discovered "Great Wall"[1] and "Great Attractor,"[2] enormous agglomerations of galaxies that attest to coherent structures stretching over half a billion light years in the present epoch. On the other hand are the new measurements of the uniformity of the cosmic microwave background, which tell us that the universe was amazingly smooth when it first became transparent—some 300 000 years after the Big Bang. The question at issue is: How did the cosmos evolve from these almost wrinkle-free beginnings to a present-day structure of such manifest inhomogeneity?

The standard hot Big Bang model, first formulated by George Gamow in the 1940s, nowadays generally incorporates the hypotheses of inflation and cold dark matter. It presumes that the density perturbations which eventually gave rise to galaxy clusters began as quantum fluctuations that were enormously stretched during the inflationary expansion phase in the first 10^{-35} sec after the Big Bang. After the universe was rendered transparent by the decoupling of radiation and matter, the standard model asserts, all further clustering of matter was due entirely to the ponderous action of gravity working against the general Hubble expansion.

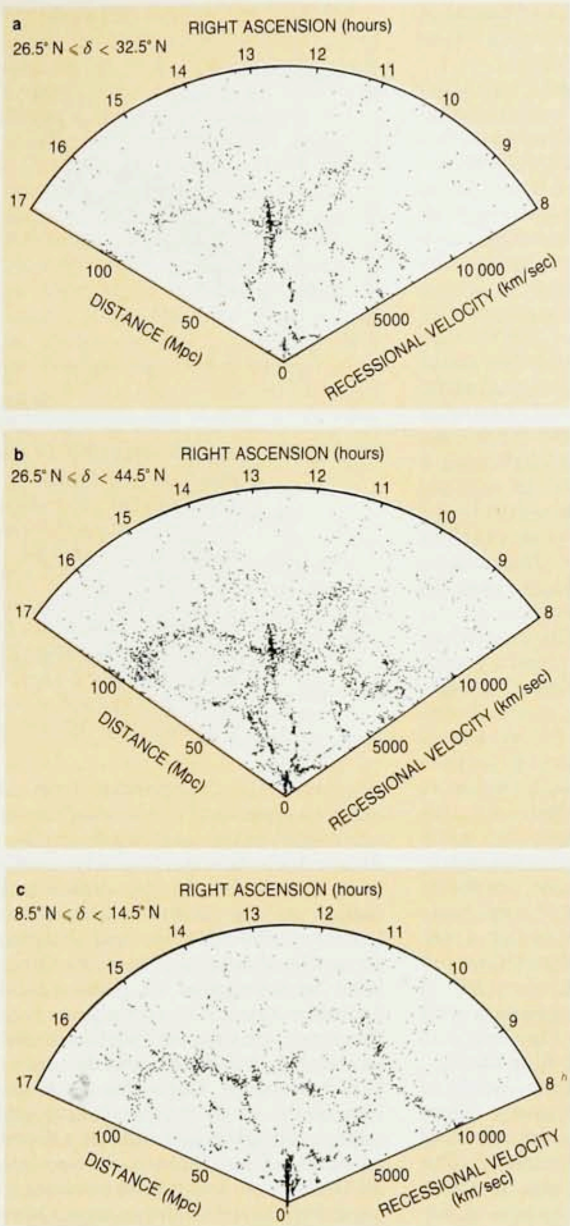
The inflationary scenario (see PHYSICS TODAY, September 1987, page 61) requires that the mean mass density of the universe be very close to its "closure" value—about 100 times the mass that can be accounted for by luminous stars. In the standard model, most of the remaining, *dark* matter is presumed to consist of weakly interacting particles whose thermal velocities would have been negligible in the epoch when structure started to develop. Hence the adjective "cold," which serves to distinguish this model from those that attribute most of the dark mass to neutrino-like particles, whose relativistic thermal motion would tend to wipe out density fluctuations.

Problems

When it was first developed in the early 1980s, inflationary cosmology was prized as the only theory that offered a causal mechanism for the origin of perturbations large enough to account for the creation and clustering of galaxies. That is to say, inflation guarantees that all the universe observable today would have grown from a primordial region small enough to be encompassed within the causal horizon defined by the speed of light. In fact, inflation is the only theory whose predictions—in particular, its initial spectrum of density perturbations—are sufficiently detailed to permit a serious confrontation with the data.

As the decade and its observing technology progressed, extensive redshift surveys accumulated more and more evidence that galaxies were clustering into structures much larger than anything the inflation theortists were expecting. Even when helped along by cold dark matter and the *ansatz* of "biased galaxy formation," computer simulations of gravitational evolution starting from the spectrum of density fluctuations left behind by inflation were unable to generate structures much larger than 30 Mpc. (A megaparsec is slighty more than 3 million light-years. All distances quoted here take the Hubble constant H_0 to be 100 km/sec per Mpc. If H_0 turns out to be smaller, all distances inferred from redshifts become correspondingly larger.)

The Great Wall, the most extended of the recently discovered megastructures, appears to stretch over 170 Mpc. In their attempts to understand



A 'Great Wall' of galaxies is suggested by these surveys of several strips of sky, using redshift as the measure of distance.[1] All the strips cover the same 9 hours of right ascension (135° of celestial longitude). The wedges shown here integrate over the indicated intervals of declination δ (celestial latitude). **a:** The original 1986 Geller–Huchra survey, covering just 6° of declination, looked like a slice through a bubbly foam. **b:** Expanding the survey an additional 12° north showed a surprising persistence of the original pattern. **c:** A new survey of galaxies in a 6° strip of declination well to the south of the earlier surveys still shows the same principal feature predominating: an irregular line stretching across the cosmic wedge at a distance from us of about 100 Mpc, suggesting a $170 \times 60 \times 5$-Mpc wall of galaxies. Radial "fingers" pointing at the origin are artifacts due to intracluster motion. **Figure 1**

the origin of such inordinate structures, theorists have come up with imaginative elaborations of the standard model involving "double inflation"[3] or very late phase transitions. Others have invoked noninflationary theories positing explosive or electrodynamic alternatives to gravity or bizarre topological defects such as cosmic strings and global texture.[4]

When the Great Wall was first reported last fall, Richard Gott and Changbom Park at Princeton undertook a computer simulation of unprecedented scale to see if they could generate so large a structure simply by gravitational clustering within the standard model. "The existing simulations," Gott told us, "just didn't have adequate size and resolution." Like most standard-model theorists these days, Gott and Park assisted the process of clustering by assuming biased galaxy formation—some nonlinear mechanism that restricts galaxy formation to regions of unusually high primordial mass density.

Having simulated 2 million galaxies and 2 million parcels of cold dark matter in a cosmic wedge 307 Mpc across, they concluded[5] that gravity has indeed had enough time to accumulate structures very much like the Great Wall. Comparing simulated distributions with observed structures is, however, a nontrivial issue requiring the development of new analytic tools. How closely the Gott–Park simulation resembles the megastructures seen in the heavens is still a matter of some debate.

The observed uniformity of the cosmic microwave background provides another useful curb on some of the more exotic theoretical speculations. But these measurements are now also coming perilously close to calling the standard model into question. The March issue of PHYSICS TODAY (page 18) showed the first maps of the microwave sky produced by the recently launched Cosmic Microwave Explorer satellite. These preliminary COBE results, with an angular resolution of 7°, show the temperature T of the microwave sky (corrected for the Doppler shift due to our motion) to be uniform to a within a part in 10^4. By the end of the year, the COBE sky maps will have reached the more interesting sensitivity level of 10^{-5}. At much finer angular resolution, recent radiotelescope measurements of selected patches of the microwave sky by Anthony Readhead and his Caltech colleagues[6] have found no fluctuations down to 2 parts in 10^5.

"The moment of truth is near," warned University of Chicago theorist Michael Turner in March at the First International Symposium on Particles, Strings and Cosmology (PASCOS-90) in Boston. "If they haven't found fluctuations on large angular scales by the time the sensitivity of the microwave measurements gets down to 3 parts in 10^6," he added somewhat hyperbolically, "we champions of the standard inflationary model will be honor bound to commit ritual suicide." The 3-kelvin cosmic microwave background is the fossil record of the universe at the moment when radiation ceased to be an important factor in the evolution of structure. If it shows no wrinkles even at the level of 3×10^{-6} in $\delta T/T$, there seems to be no way that gravitational evolution within the standard model could have produced galactic clusters, not to mention megaclusters, a mere 10 or 20 billion years later.

The Great Wall

Four years ago Valerie de Lapparent, Margaret Geller and John Huchra of the Harvard–Smithsonian Center for Astrophysics reported the results of a pioneering redshift survey of all the galaxies brighter than magnitude 15.5 in a long, thin strip of sky centered on the well-known cluster of galaxies in the constellation Coma Berenices. The strip covered a full 9 hours of right ascension ($9 \times 15°$ of celestial longitude about the North Star) but only 6° of declination (celestial latitude). Redshift was to supply the third dimension, namely distance from us. The brightness cutoff provided a reasonably unbiased census of the galaxies in a cosmic wedge out to distances of about 100 Mpc.

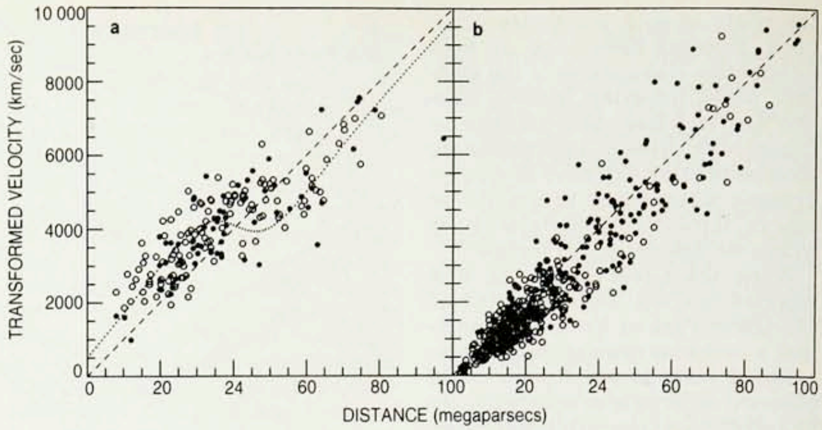
This ambitious mapping attracted attention because it showed a distribution that looked like a slice through a foam of soap suds. (See PHYSICS TODAY, May 1986, page 17, and figure 1a on page 21.) The galaxies appeared to be crowded along the perimeters of a jumble of contiguous, irregular circles, some as large as 50 Mpc across. To investigate this foam properly in three dimensions, Geller and Huchra next surveyed two more 6°×9 hr strips of sky just north of the original strip. Instead of the waxing and waning of circle sizes they expected for successive slices though a foam, they found a surprising persistence of the original pattern from one cosmic wedge to the next—more suggestive of sheets than bubbles. (See figure 1b.) "The bubbles turned out to be much bigger than we expected," recalls Geller.

The clincher came last year when Geller and Huchra surveyed a fourth 6°×9-hr strip of the celestial sphere, this one far enough south of the original strip that they did not expect to see any residual trace of its bubbles. It turned out that the most prominent feature exhibited by this new map (figure 1c) was the same long, irregular line of galaxies clearly seen in the three more northerly wedges. Stretching over the full east–west extent of each wedge at a distance of roughly 100 Mpc, this striking feature, persisting over 36° of declination, strongly suggests a wall of galaxies *at least* 170 Mpc long and 60 Mpc high, but only 5 Mpc thick.

"The Great Wall," they wrote of their newly named discovery, "demonstrates one of the most sobering results of large redshift surveys: The size of the largest structures we detect is limited only by the extent of the survey."[1] It is almost an axiom of cosmology that the universe, at sufficiently large scale, is homogeneous and isotropic. It seems we have not yet seen a sample of the universe large enough to exhibit its "average" character. As Turner puts it, "To first approximation, all measurements in cosmology are impossible."

Peculiar motions

Measuring a galaxy's redshift is not the only way to determine its distance. Indeed redshift can be deceptive, because galaxies can have "peculiar motions" in addition to their participation in the general Hubble expansion of the universe. Gravitational interactions within large clusters are well known to give rise to peculiar motions that show up as



Hubble diagrams of velocity vs distance for galaxies in the direction of the putative Great Attractor (**a**) and galaxies in other directions (**b**) . The velocities, measured by redshift, have been transformed into the frame in which the cosmic microwave background is isotropic. Distances to spiral galaxies (open circles) are measured by the Tully–Fisher method, and to ellipticals (dots) by a revised Faber–Jackson method. The random clustering around the diagonal in **b** indicates the expected Hubble flow. But in **a**, nearer galaxies are receding faster than the Hubble rate, while more distant galaxies recede slower. These data appear to follow the S-curve prediction (dotted) of a model that assumes a Great Attractor centered some 40 Mpc away from us. **Figure 2**

"fingers of God"—spurious lines of galaxies appearing to point back at us on redshift maps, as if in admonition. Figure 1 shows a particularly prominent finger, due to the gravitating motion of the galaxies within the Coma cluster. Geller and Huchra stress the observation that the Great Wall is orthogonal to these radial fingers, making it quite unlikely that this structure is an artifact of reliance on redshift as a measure of distance.

If one could know the intrinsic luminosity of a distant galaxy, its apparent brightness would be a direct measure of its distance. In the late 1970s two such techniques were developed, both based on the general observation that the typical velocity of internal movement within a galaxy increases rapidly with its size. For spiral galaxies, Brent Tully (University of Hawaii) and Richard Fisher (National Radio Astronomy Observatory, Green Bank, Virginia) found a very useful empirical relation between the intrinsic luminosity of a spiral galaxy and the rotational velocity of its outer reaches as measured by the Doppler broadening and splitting of its 21-cm hydrogen hyperfine line.

The Tully–Fisher relation cannot, however, be used to determine the intrinsic luminosity of *elliptical* galaxies, because ellipticals do not have enough interstellar gas, and they don't rotate very fast. For elliptical galaxies Sandra Faber and Robert Jackson at the University of California, Santa Cruz, developed an alternative trick. They found that one could determine intrinsic luminosity from the dispersion of stellar velocities near the galactic core, as measured by the Doppler broadening of various stellar absorption lines. With either the Tully–Fisher or the Faber–Jackson technique, taken together with measurements of the overall redshift and apparent brightness of a galaxy, one can determine, to some extent, whether that galaxy is receding faster or slower than the Hubble law predicts for its distance.

It is generally assumed that a "comoving observer"—one who simply rides along on the overall Hubble expansion without any peculiar motion—would see an isotropic cosmic microwave bagkground. From the well-measured dipole anisotropy of the microwave background as seen from the Earth, it is clear that we are traveling through the cosmos with a peculiar velocity of about 600 km/sec. The microwave sky is 0.2% hotter in the direction of this motion than in the opposite direction. Until recently the peculiar motion of our galaxy and its neighbors was attributed simply to the gravitational attraction of the nearby Virgo cluster of galaxies. It was assumed that if one looked farther afield, well beyond the reach of the Virgo cluster, one would see no correlated pattern of peculiar motions. At scales larger than about 50 Mpc, it was believed, the cosmos would look isotropic.

The Great Attractor

Since 1986, Faber and six collaborators with access to optical telescopes in the Northern and Southern Hemispheres have been subverting this comfortable presumption of large-scale isotropy by means of extensive galactic-distance surveys. (See PHYSICS TODAY, October 1987, page 17.) The group, which for some reason came to be known as "The Seven Samurai," measured the brightness, redshift and stellar velocity dispersion of some 400 elliptical galaxies across the sky out to 60 Mpc. Then they transformed the recessional redshift velocities into the comoving cosmic reference frame simply by subtracting off our own peculiar velocity as measured by the microwave dipole asymmetry. They plotted these corrected velocities against Faber–Jackson distance, expecting to see the isotropic Hubble expansion pattern, perturbed by peculiar motions correlated only on local scales. What they found instead was a large-scale bulk flow of the galaxies, a general streaming more or less in concert with our own peculiar motion.

By 1987 the Samurai had concluded that this general streaming was due to the gravitational pull exerted by an enormous region overdense with galaxies, whose center was some 40 Mpc from us in the general direction of the Hydra–Centaurus supercluster, somewhat to the south of the Virgo cluster. They called this object The Great Attractor. Computer models yielded a diameter of about 80 Mpc and a mass of 3×10^{16} Suns. That would be the mass of tens of thousands of typical galaxies, including the dark matter one infers from the dynamics of galaxies. The Great Attractor incorporates not only the Hydra–Centaurus supercluster, but also another supercluster that stretches between the the constellations Indus and Pavo near the south celestial pole. We seem to be sitting close to the outer margin of the Great Attractor.

The Great Attractor has, over the years, also attracted its share of skeptics. But now we have a view from the far side that makes it harder to doubt its reality. At this year's meeting of the American Astronomical Society, in Washington, DC, Alan Dressler (Carnegie Institution of Washington), one of the original Samurai, reported that he and Faber had finally succeeded in observing the "backside infall" of galaxies into the far side of the Great Attractor.

The old Samurai sample of elliptical galaxies did not extend as far as the putative center of the Great Attractor. In 1988 Dressler and Faber undertook to extend the measurements through the very heart of the beast, availing themselves of spiral as well as elliptical galaxies. Spiral galaxies, because they cluster less than ellipticals, are thought to offer a less biased view of the cosmic distribution of galaxies. Furthermore, Tully–Fisher distance determinations are thought to be somewhat more reliable than distances obtained by the Faber–Jackson technique. But the traditional 21-cm Tully–Fisher method would have limited Dressler and Faber to the largest radiotelescopes. Therefore Faber and her Santa Cruz colleague Stephane Courteau developed an optical variation on the Tully–Fisher method: Instead of measuring the broadening of the 21-cm hydrogen microwave line, they undertook to measure the rotation velocity of a spiral galaxy by the variation of the Doppler shift of the red H_α line across the width of the galaxy.

At the Washington AAS meeting Dressler presented the recent H_α measurements of 125 spiral galaxies extending all the way out to 80 Mpc in the direction of the Great Attractor, essentially to its far end. Taken together with the earlier measurements of elliptical galaxies, these new data offer a striking confirmation of the large-scale coherent flow engendered by the tug of the Great Attractor. Dressler showed the Hubble diagram reproduced in figure 2a. In the absence of coherent peculiar motion, this plot of redshift velocity (corrected for our peculiar motion) against independently measured distance should simply show all the galaxies concentrated, with random spread, along the diagonal that describes the Hubble expansion (as in figure 2b). What we see instead for these 273 galaxies is an S-shaped distribution crossing the Hubble diagonal at about 43 Mpc. That is to say, when we look in the direction of the Great Attractor, galaxies closer to us than about 43 Mpc tend to recede faster than the general Hubble expansion and galaxies farther out, at least to a distance of 80 Mpc, are receding too slowly.

That is precisely what one would expect if the Hubble expansion is being retarded by an enormous overdensity of galaxies centered at a distance of 43 Mpc. The data are in surprisingly good accord with the dotted S curve in figure 2a, which is calculated from a simple, spherically symmetrical model of the Great Attractor proposed two years ago by Faber and David Burstein (Arizona State University), another of the Samurai. The Great Attractor, it would seem, is seriously distorting the Hubble expansion of the universe over a volume of about a million cubic megaparsecs in our neighborhood.

In another talk at the AAS meeting, Robert Schommer (Rutgers) presented similar results. His Rutgers–Michigan–Caltech collaboration is also beginning to see infall from the far side of the Great Attractor. But they would place its center somewhat farther out—at about 52 Mpc.

'Less than zero'

The Geller–Huchra and Dressler–Faber surveys do not go out much past 100 Mpc. What sort of structure might one see at much greater distances? The recently published result[7] of a very narrow and deep redshift survey by Thomas Broadhurst (University of Durham, England) and his collaborators suggests a very puzzling possibility. They have measured galaxy redshifts out to 2000 Mpc in two narrow, "pencil beam" regions near the north and south poles of our galaxy, where obscuration from local dust is minimal.

What they seem to see is a possibly periodic oscillation of density with distance, all the way out to 2000 Mpc. The first maximum they come to is a piece of the Great Wall. So perhaps the Wall is a very typical feature of the cosmos. The Fourier spectrum of these oscillations peaks sharply at a spacing of 128 Mpc. It's as if the galaxies are mostly confined to regularly spaced sheets or bubbles.

"Our results are tentative," the authors caution, "and possibly unappealing in terms of standard cosmologies." The paper carefully avoids the word *periodic*. Commenting on the Broadhurst results in the same issue of *Nature*, Berkeley astronomer Marc Davis is more blunt. "If the distribution is truly periodic," he writes, " it is safe to say we understand less than zero about the early universe."

—BERTRAM SCHWARZSCHILD

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