

Superclusters and the large-scale structure of the Universe

From the beginning of this century, study of the origin and evolution of the Universe has been informed by the Cosmological Principle: The Universe is homogeneous and isotropic. On the largest observable scale, that of the blackbody cosmic background radiation, this statement has been confirmed to a high degree of accuracy; spatial inhomogeneities in the temperature of the background radiation are less than 1 part in 10^4 . On the human scale, the Principle is patently absurd. A question of considerable current interest is to ascertain on what scale the postulate breaks down. Observers have recently been working hard on mapping structure on scales of 10^6 to 3×10^8 light years, and theorists have been exploiting the increasingly important connections between particle physics and cosmology in an attempt to understand how these structures come to be.

First there were galaxies. In the 1920s and 1930s Kant's "Island Universes" were established as distinct dynamical systems with masses around $10^{11} M_{\odot}$ and scale sizes on the order of 10^5 light years. It was also recognized early on that the distribution of these galaxies on the sky was non-random and that large clusters, containing hundreds of galactic objects within a radius of around $10^{6.5}$ ly, appeared to be gravitationally bound systems. More recently, superclusters—aggregates of several clusters spanning roughly $10^{7.5}$ ly—have been identified. On the other hand, we have also learned in the last decade that this hierarchy does not continue indefinitely—the cosmic background radiation is highly isotropic, implying homogeneity on the scale size of the observable Universe ($\sim 2 \times 10^{10}$ ly).

The first quantitative investigation of large-scale structure was begun over a decade ago by James Peebles and his collaborators at Princeton.¹ Using catalogs of galaxy positions compiled over the previous two decades, he defined a statistical two-point correlation function to describe the clumpiness of galaxies in two dimensions; the correlation function is a power law, decreasing

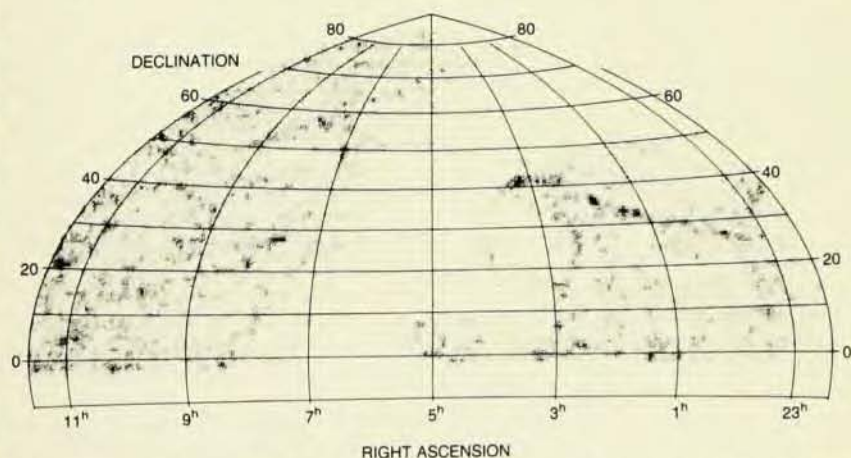
with a slope of -0.8 as the scale size increases. This statistic is a fundamental constraint on all models concerned with how the large-scale structure arose.

Redshift surveys. The obvious extension of this early work was to move on to the third dimension. To determine the distance of a galaxy is considerably more difficult than determining its position on the sky, however; a spectrum must be obtained for each object (requiring about 10 minutes to an hour of telescope time) from which the recession velocity v , or redshift, is computed. The distance D then follows from the recession law $v = HD$, where H is the Hubble constant, thought to be in the range 15–40 km/sec per million light years. Systematic redshift surveys were begun about five years ago as high-efficiency, photon-counting spectrometers became available on an increasing number of telescopes. The results of one project published two years ago² by Robert Kirshner (University of Michigan), Augustus Oemler (Yale), Paul Schechter and Stephen Schectman (Mount Wilson) revealed a striking gap in the redshift distribution

at three different locations in the northern sky, suggesting a void in the distribution of galaxies nearly 3×10^8 ly across (see PHYSICS TODAY, January 1982, page 17).

In following up this discovery, Kirshner told us that his group has now obtained redshifts for a complete magnitude-limited sample from a grid of 282 fields, each 15 square arcminutes in size, interior to the triangle formed by the original survey regions. The 231 galaxies found assiduously avoid the velocity range 12 000 to 18 000 km/sec throughout the area, although it now appears that the original three regions are at the very edge, or perhaps even just outside, this void. Other workers^{3,4} have claimed to find emission-line galaxies within the original triangle, but Kirshner claims that none lie within the newly defined empty region centered at $14^h 48^m$ and $+47^\circ$. The density of galaxies in this 10^7 million cubic light year void is a factor of more than about 4 lower than in the surrounding areas.

In a complementary redshift survey covering most of the northern hemisphere, but to a much brighter limiting



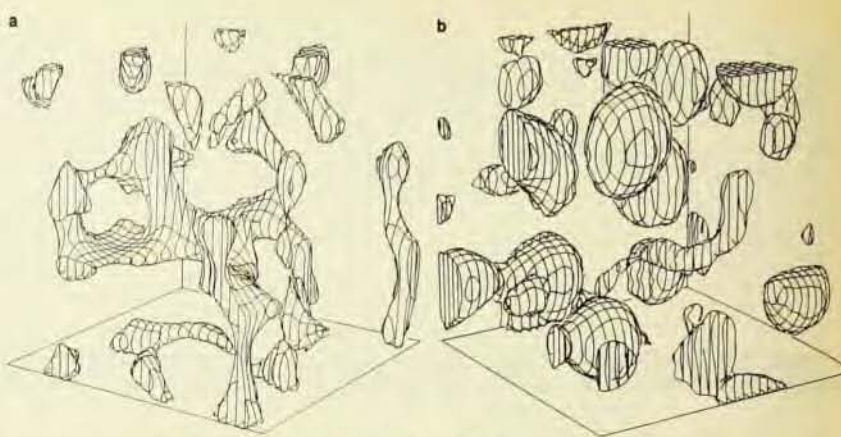
Two-dimensional distribution of galaxies shown on an equal-area projection of a portion of the celestial sphere. The long filament stretching from 23^h to 3^h has been shown by Riccardo Giovanelli and Martha Haynes to contain chiefly galaxies in the redshift range from 3000 to 5300 km/sec, indicating that this Perseus-Pisces supercluster is a true, three-dimensional structure with a large density enhancement over the surrounding regions. The apparently empty band extending down from the northwest is due to obscuring dust in the plane of our Galaxy.

magnitude, Marc Davis (now at the University of California, Berkeley), John Huchra, and David Latham of the Harvard Center for Astrophysics have measured recessional velocities for 2400 galaxies.⁵ Although apparent large-scale structure is visible in a three-dimensional representation of the survey results, Davis feels that recent discussion of extensive filaments and voids has been somewhat overplayed. He notes that it had been thought that the three-dimensional clustering of galaxies would change Peebles's two-point correlation function if it were extended to a third dimension; this, however has not proven to be the case—the expected slope for the correlation in three dimensions, -1.8 , is just that found when the analysis is applied to the CFA survey data.⁶

Radio surveys. Optical spectroscopy is not the only way to obtain the recessional velocity of a galaxy. For spiral galaxies that have a large amount of neutral hydrogen gas, 21-cm radio observations yield a redshift just as readily, with the added advantage that a galaxy mass determination is obtained simultaneously from the width of the observed line profile. Riccardo Giovanelli (Arecibo), Martha Haynes (National Radio Astronomy Observatory) and Guido Chincarini (University of Oklahoma) have recently been compiling large redshift samples using the 21-cm line receivers of the Arecibo Observatory in Puerto Rico and the NRAO 92-m dish at Green Bank, West Virginia. For example, a total of 1500 new redshifts have been obtained between 22^h and 4^h in the Arecibo telescope's declination range of 0° to $+38^\circ$.

The project was conceived in part to "see whether or not the long filaments seen in the two-dimensional galaxy plots are Martian canals," according to Giovanelli. Apparently, they are not. Haynes told us that the redshifts for galaxies in this region are very strongly peaked near 5000 km/sec, and that the velocity dispersion of the galaxies along the ridges is very small (< 200 km/sec). At the International Astronomical Union Symposium in Crete last year on the Large Scale Structure of the Universe, the group reported that the detailed structure of the Pisces-Perseus supercluster in this region "appears as a maze of thin filamentary structures which maintain a high degree of spatial coherence."⁷ The axial ratio of these approximately 200-million-ly-long filaments is greater than 10, with volume density contrasts of up to a factor of 100, and total masses of about $10^{16} M_\odot$.

In yet another interesting approach to the large-scale structure problem, Neta Bahcall and Raymond Soneira (Princeton University and the Institute



Three-dimensional simulation of clusters (left) and voids (right) in a neutrino-dominated Universe by Joan Centrella and Adrian Mellot, simulating a million galaxies on a Livermore Cray 1. At left, the contours indicate clustering into filaments and pancakes by enclosing all regions with more than twice the present mean density of galaxies. At right, voids are indicated by contours enclosing all regions with less than half the present mean density.

for Advanced Study) have taken a step up in scale to examine the cluster-cluster (rather than galaxy-galaxy) two-point correlation function. Their sample includes more than 100 rich clusters for which redshift information is available from recent complete surveys. The surprising result is that, while the slope of the correlation is the same as that found for galaxies (-1.8), the strength of the correlation is some 15 times stronger.⁸

This result has been found independently by Kyplin and Kopylov (Moscow) and is further supported by an extension of the analysis to the full ~ 2000 -entry cluster catalog for which only two-dimensional angular correlations can be computed. Thus, whereas the galaxy-galaxy correlation becomes noise-dominated at about 5×10^7 ly, the coherent structure can now be followed to scales nearly 10 times larger. More recently, Bahcall and Soneira have also used the redshift survey data to compile a catalog of superclusters in three dimensions containing about 20 members. Interestingly, they find that the two largest superclusters in the northern hemisphere lie on the front and back sides, respectively, of the large void found by Kirshner and his collaborators. Finally, at a COSPAR/IAU symposium in Bulgaria in July, Bahcall reported on a vast region covering nearly $\frac{1}{3}$ of the northern sky in the galactic anticenter direction that is apparently totally devoid of rich clusters; the scale size of this feature is about 10^9 ly.

Missing mass. It is becoming increasingly clear, then, that the matter we can see is inhomogeneous on very large scales. A crucial question remains: Does this luminous matter accurately trace the total mass distribution of the Universe? Just 50 years ago, Fritz Zwicky noted that the galaxies in the

nearby rich Coma cluster had a velocity dispersion suggesting that the gravitational potential in which they moved was considerably deeper than that computed by simply summing the masses of the visible members. This "missing mass" problem has been with astronomers ever since, and its solution is crucial in reaching an understanding of how the observed large-scale density fluctuations were formed.

The magnitude of the problem is usually expressed in terms of the parameter Ω , the ratio of observed mass density ρ to the critical mass density ρ_{crit} necessary to close the Universe; for $\Omega = 1$, the total mass of the Universe is just sufficient to stop the current expansion at $t = \infty$. The luminous baryonic matter we see in the form of galaxies yields a value of Ω near 0.01. Numerous studies over the past two decades of individual galaxy rotation curves, binary galaxy orbits and group and cluster velocity dispersions strongly suggest that galaxies possess massive dark halos containing ≥ 10 times the mass of their luminous material. Some authors have suggested that the amount of dark matter increases with increasing size scale and that the velocity dispersions of rich clusters and superclusters require Ω to be around 0.5 to 1.

Much of this work, however, was done before the extensive new redshift catalogs became available, and cluster velocity dispersions were often determined from only a handful of bright galaxies. The detailed cluster studies of the CFA group are now showing that many of these large systems contain complex substructure and are not yet in dynamical equilibrium; thus, mass estimates that have assumed such equilibrium need revision. Margaret Geller (CFA) told us that, beyond a scale of $\sim 5 \times 10^5$ ly (corresponding to

roughly one galaxy rotation per Hubble time), she sees little evidence for an increasing amount of dark mass. She suggests that, from dynamical studies of galaxy clusters, at least, there is no evidence for a value of $\Omega > 0.2$. This value is comparable to the theoretical upper limit on the baryonic component of the Universe derived from calculations of primordial nucleosynthesis. To avoid overproducing deuterium in the Big Bang, Ω_{baryon} must be less than about 0.2; recent results on the primordial lithium abundance suggest an even lower limit on Ω_{baryon} of about 0.15.

Many cosmologists today, however, take it as an article of faith that $\Omega = 1$ (see David Schramm's discussion of the flatness problem in *PHYSICS TODAY*, April, page 27), and in the new "inflationary" models Ω must be unity to a high degree of precision. If this is the case, we must ask what it is that dominates the mass density of the Universe. The larger-scale structure we are now observing places an important constraint on the possibilities.

One popular candidate for the missing mass has been neutrinos. There are about 100 low-energy neutrinos and antineutrinos per cm^3 in the Universe today, and if each had a mass around 30 eV, they would provide the closure density. The fact that they interact so weakly, however, results in what some regard as a problem in producing our current, highly structured Universe. At early times, while the neutrinos are relativistic, any perturbations in their density distribution are quickly damped out as they stream freely out of overdense regions on all scales out to the local horizon. When the Universe has cooled to a temperature near 10 eV (at a redshift $z \sim 3 \times 10^4$), these neutrinos become nonrelativistic and they can clump; any density fluctuations that exist at that epoch can then grow and form potential wells into which the baryonic matter can fall at much later times after it decouples from the radiation field (at $z \sim 10^3$). However, the free-streaming neutrinos have erased any fluctuations on scales smaller than about 10^5 ly corresponding to masses around 10^{15} to $10^{16} M_{\odot}$. In this picture, then, $10^{15} M_{\odot}$ is the natural scale on which structure forms.

This scale is just that required for the "pancake" (or, perhaps more appropriately, "blini") model of large-scale structure originated more than ten years ago by Ya. B. Zel'dovich (Institute of Applied Mathematics, Moscow). In this picture, the largest scale structures (clusters and superclusters) form first, collapsing into flat sheets and then fragmenting into smaller subclusters and, eventually, galaxies. A recent refinement of the model by Zel'dovich and his colleagues indicates that the

galaxy density should be highest along intersecting lines and sheets, very similar to the structure reported from the recent redshift surveys.⁹

The model, however, is not without difficulties. Because the initial perturbations when the baryons decouple must have an amplitude less than 10^{-4} to avoid violating the constraint imposed by the isotropy of the cosmic background radiation, the $10^{15} M_{\odot}$ pancakes don't become unstable to fragmentation into smaller structures until quite late ($z \sim 3$ to 10). This is uncomfortably close to the epoch at which we observe galaxies (as quasars) to be extant.

A comprehensive series of numerical simulations recently carried out by Simon White, Carlos Frenk and Marc Davis (Berkeley)¹⁰ casts further doubt on the neutrino-dominated scenario. Using as constraints the observed limits on Ω , H , and the temperature of the background radiation, they are unable to produce the correct slope of the two-point correlation function and also produce galaxies early enough to satisfy the observations. To get the correct slope, the proper time for pancake formation is the present (in other words, much too late), while if pancaking is forced to occur just before the epoch at which we see the most distant galaxies ($z \sim 4$), other parameters such as Ω and H are forced outside of acceptable bounds. As Davis put it, "the neutrino theory is falsifiable" and, he believes, is on the verge of being discarded.

Anatoli Klipin and Sergei Shandarin (Institute of Applied Mathematics, Moscow) and Joan Centrella (University of Illinois) and Adrian Melott (University of Pittsburgh) have also conducted such numerical experiments and have found similar problems. Melott is exploring one possible solution by adding dissipation in the simulation of the baryonic matter as it moves in the neutrino-dominated potentials. He reports that the emergent structure can be strongly affected; further work with more realistic hydrodynamics is needed. Growing doubts about the experimental evidence for a non-zero neutrino mass have however diminished interest in these models.

In the past year, as a result of the increasingly apparent confluence of particle physics and cosmology, a new set of candidates for the missing mass have emerged: the axion, the theoretical particle conceived to solve the problem of the lack of CP violation in strong interactions, and the gravitino, photino, and other particles required by supersymmetric theories. The critical difference between a neutrino-dominated Universe and one where most of the mass is in one of these new, exotic particles is the epoch at which

the particles become nonrelativistic and gravitational clumping can occur. As noted above, this time sets a lower limit on the mass scale of perturbations; for a particle such as the gravitino with a mass near 1 keV, the limit falls below $10^{12} M_{\odot}$ (the size of a galaxy) whereas for axions, the limit is much less than $1 M_{\odot}$. Thus, each type of particle results in a different processing of the initial mass-fluctuation spectrum, leading, in principle, to a new diagnostic for the missing mass based on the present large-scale structure.

The initial fluctuation spectrum has, until recently, been a completely free parameter, severely limiting the utility of this diagnostic. Early simulations by Peebles had simply assumed a white noise spectrum (equal power at all scales) in an attempt to reproduce the observed hierarchical clustering and the proper slope for the two-point correlation function. The new inflationary universe models, however, fix the initial spectrum; evolving this with, say, an axion-dominated mass density yields a much "redder" fluctuation spectrum with more power on larger scales. In a recent review talk at the June meeting of the American Astronomical Society in St. Paul, Michael Turner (University of Chicago) dubbed this "non-traditional hierarchical clustering." The Berkeley group and Melott and his collaborators¹¹ have recently run simulations of axion-dominated inflationary universes using reasonable values of Ω and H ; these reproduce the observed large-scale structure very well, while at the same time giving the correct value for the two-point correlation function slope and forming galaxies early enough to satisfy the observational constraints. All are agreed that the approach is a promising one for producing a model universe like the real one we observe.

Future theoretical work will see larger simulations with greater spatial resolution as well as the inclusion of more realistic hydrodynamics in following the behavior of the baryonic matter. In addition, there is the need for a good statistic to quantify the three-dimensional structure we observe so that more quantitative tests of the simulations are possible. The observers are unanimous in the need for larger, deeper redshift samples to better define the three-dimensional structure of the luminous matter on all scales. The Space Telescope will be an extremely important tool for structure studies. Through sensitive searches for non-luminous gas clouds in the apparent voids it will determine the degree to which the galaxies trace the true mass distribution, and it will allow for much deeper redshift surveys, albeit in spatially limited fields.

As Davis notes, as far as the dynam-

ics of its constituents are concerned, "the Universe is an unusual system in that it is very slow to forget its initial conditions." Its large-scale structure is one important result of those initial conditions, and we have only just begun to mine the wealth of information it contains.

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Novel laser for fiber-optic communication

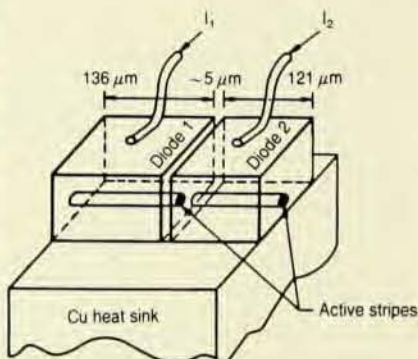
A new kind of semiconductor laser, developed by Won-Tien Tsang and his colleagues at Bell Labs, has demonstrated a number of remarkable capabilities that promise to be of considerable importance for fiber-optic communication. This cleaved-coupled-cavity semiconductor laser, nicknamed the C^3 laser, is able to generate essentially monochromatic pulses of infrared light at repetition rates in excess of a gigahertz. Furthermore, one can electronically switch this pulsed monochromatic output from one wavelength to another on a nanosecond time scale.

In the infrared wavelength regime suitable for long-distance fiber-optic communication (1.3 to 1.6 microns), the pulsed output of conventional semiconductor diode lasers has a wavelength spread of about fifty or a hundred angstroms. This spectral width presents dispersion problems that severely limit the rate of data transmission and the distance over which one can transmit information without reamplification. One is faced with a trade-off. Single-mode silica optical fibers are most transparent at 1.55 microns. But at this wavelength the fibers suffer from considerable dispersion. Different frequency components of the pulse travel at different speeds, eventually washing out the signal structure and thus limiting the rate at which one can send information over long distances. If one chooses, on the other hand, to transmit information at a wavelength of 1.3 microns, dispersion is minimal. But at 1.3 microns the fiber is significantly less transparent, making it necessary to reamplify the signal along its way more often than one would like.

The new C^3 laser, developed by Tsang, Anders Olsson and Ralph Logan, uses¹ a coupled-cavity resonance technique to get rid of all but one of the half dozen or so Fabry-Perot modes that are responsible for the spectral width of a conventional single-cavity

diode laser. The result is a pulsed output with a spectral width of less than an angstrom at gigahertz rates of amplitude modulation. With this extraordinarily monochromatic pulsed output one can forget about dispersion and transmit data at a wavelength of 1.55 microns, where the optical fibers are at their clearest. Thus Bell Labs has recently demonstrated² the transmission of digital information at a rate of 10^9 bits/second over 104 kilometers of optical fiber, with an error rate of less than 1 in 10^9 and no reamplification along the way. At this rate, Tsang likes to point out, one can transmit the entire text of the *Encyclopedia Britannica* in less than half a second.

This impressive long-distance, high-rate demonstration was done at a fixed



The cleaved-coupled-cavity semiconductor diode laser with which the Bells Labs group demonstrated gigahertz frequency switching in the 1.3-micron wavelength regime. Laser light is reflected back and forth across the 5-micron air gap between the GaInAsP active stripes of the two diodes, so that only the resonant mode common to both cavity lengths is reinforced, producing monochromatic output pulses at gigahertz repetition rates. Fine tuning and frequency switching are accomplished by independently varying the injector currents, I_1 and I_2 , in the two diodes.

infrared frequency, with pulse amplitude modulation providing the binary information. But the C^3 laser offers an alternative method of encoding digital data that can enhance the information transfer rate still further. At a gigahertz rate one can switch the output wavelength among as many as a dozen modes spaced about 20 Å apart. Thus, instead of single-frequency transmission with low- and high-power pulses representing binary 0 and 1, respectively, one could simply switch between two frequencies. Switching among four (or eight) frequencies would yield pulses with twice (or three times) the information content of a binary bit.

The **cleaved-coupled-cavity** laser is made by cleaving a conventional semiconductor diode laser along a crystal plane parallel to its end faces to produce two shorter diode lasers of slightly different length. Starting, for example, with a GaInAsP laser 250 microns long, one might end up with two lasers with lengths of 130 and 120 microns. It turns out, contrary to the pessimistic expectations of many, that the precise difference between the two lengths doesn't matter. One can therefore mass-produce the C^3 laser by conventional fabrication techniques without having to worry about the exact point of cleavage.

Each of these half-length diodes in isolation would behave like a conventional semiconductor laser. Its two end faces would serve as the mirrors of a Fabry-Perot interferometer cavity, supporting only those lasing modes for which the diode's length is an integral multiple of half the wavelength. About half a dozen such Fabry-Perot modes, spaced roughly 20 Å apart, would generate a laser output with a spectral width of more than a hundred angstroms.

The trick of the C^3 laser is to suppress all but one of these modes by coupling the two half-length diodes together optically. The cleaving is done with the original diode fixed on a substrate film, so that the active lasing strips of the resulting short diodes will be precisely aligned, with an air gap of about 5 microns between them. Thus the laser light is reflected back and forth between their active stripes.

Because their lengths are slightly different, the Fabry-Perot mode spacings of the two coupled laser cavities will differ; their lasing modes will not, in general, overlap. If, for example, the lengths of the two diodes differ by 10%, only every tenth Fabry-Perot mode can be the same in both cavities. (Think of a Vernier scale.) The coupled laser system will support only these *common* resonant modes. A lasing mode in one diode that does not correspond to a Fabry-Perot mode of the other will not be coherently reinforced. With com-