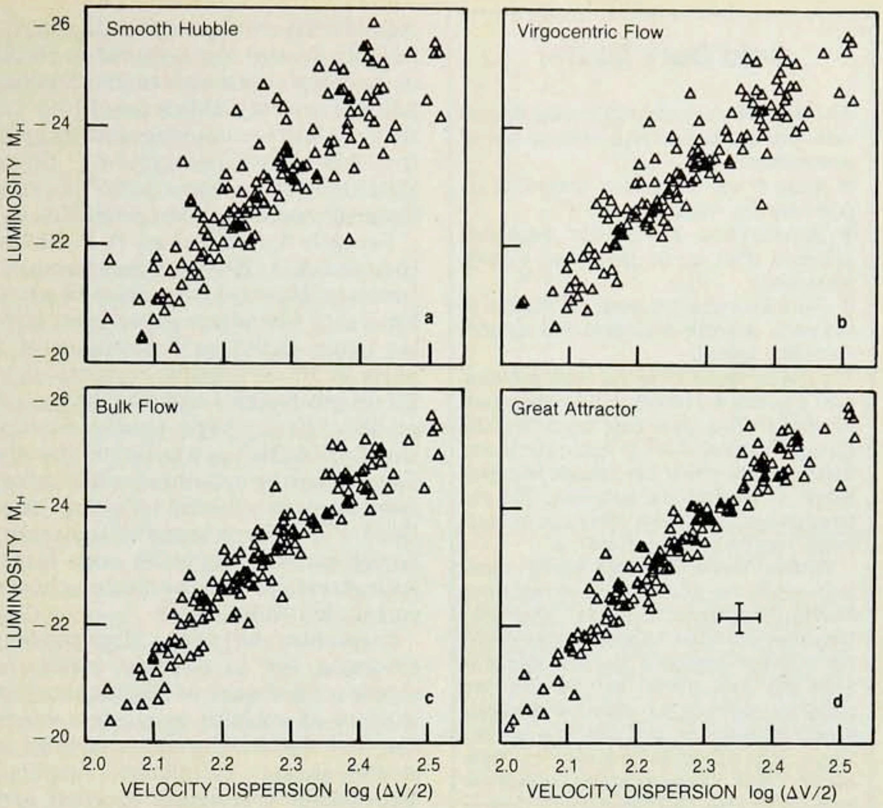
Model fits using the 150 best-observed spirals from a survey by Marc Aaronson, John Huchra, Jeremy Mould, Paul Schechter and Brent Tully (Astrophys. J. **258**, 64, 1982) show progressive improvements in the scatter of the infrared Tully–Fisher correlation that is a distance indicator for spiral galaxies: Infrared luminosity (in absolute magnitude, M_H) correlates with spectral linewidth (given as $\Delta V/2$ in km/sec) of 21-cm neutral hydrogen. The models are: (a) a smooth Hubble flow; (b) a Virgocentric infall with motion of 250 km/sec at our position in the Local Group; (c) bulk motion of 400 km/sec and a Virgocentric motion of 200 km/sec; (d) mass-concentration (great attractor) model including motion of 570 km/sec at our position and a Virgocentric motion of 200 km/sec. (From results presented at a recent meeting in Hungary courtesy of David Burstein, Arizona State.)



which we had supposed to be at rest in comoving coordinates, proved to be moving, just as the seven samurai say they are," Mould tells us. "Originally they claimed that the whole of their sample was in bulk motion. This was in conflict with our Arecibo results. But now they are talking about a concentration of peculiar velocities in the Hydra–Centaurus region, and we now see that too."

"From a smooth velocity field in 1978, to Virgocentric motion in 1982, to a motion of the Local Group and Virgo in 1986, to a large-scale velocity field in 1987, each time the previous results were incorporated in a more comprehensive model. The bottom-line for any model is its predictive power," says Burstein. "Does our model improve the scatter in the Tully–Fisher relation for spirals if we use the Aaronson data?—Yes." (See the figure at right.)

"There are very few people who are skeptical now regarding the interpretation of the observations indicating cosmic drift," Joseph Silk (Berkeley) tells us. "The recent observations are very good." Although theorists find the streaming observations plausible, the great attractor is too large to be reconciled with the cold dark matter theory of galaxy formation (see Silk's article in PHYSICS TODAY, April, page 28 and the following news story).

—PER H. ANDERSEN

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Large-scale structure, streaming and galaxy formation

"Observational results indicating large-scale streaming motions in the universe might be real giant-killers of theories," says theorist Richard Bond (Canadian Institute for Theoretical Astrophysics). (See news story on page 17.) Models based on the inflationary paradigm (see Andrei Linde's article in PHYSICS TODAY, September, page 61) are severely strained by the recent observations, Bond told us: "If true, the large-scale streaming puts in jeopardy the assumed initial spectrum of density fluctuations coming out of inflation. But the microwave background is, I think, ultimately the best probe of fluctuations and structure."

Recent theoretical models of galaxy formation have relied on dark matter and two alternative sets of initial conditions

- ▶ inflation-generated scale-invariant fluctuations—those without any initial length scale (see the box on page 20)
- ▶ fluctuations driven by cosmic strings (topological defects from the early universe).

Another idea, developed by Jeremiah Ostriker (Princeton) and others, is an explosion model in which matter gets pushed from the center of a bubble and rearranged locally (see PHYSICS TODAY, May 1986, page 17). But both large-scale fluctuations in gravitational fields and velocity fields are small in amplitude, inconsistent with large-scale streaming.

The microwave background anisotropy should tell us about density fluctuation levels coming out of the Big Bang and constrain galaxy formation scenarios.

Earlier this year in Tenerife, Rod Davies (Jodrell Bank, University of Manchester, UK), Anthony Lasenby (Mullard Radio Astronomy Observatory, Cambridge, UK) and coworkers[1] used a frequency of about 10 gigahertz on a small radiotelescope with an 8°–10° field to find temperature fluctuations of 3.7 parts in 10^5 in the sky signal. They could subtract out Galactic emission because of its spectral shape: Because they did not observe the greater emission expected at the lower frequency of 5 gigahertz, they concluded that Galactic emission was not the origin of the fluctuations. Their observation is inconsistent with the cold dark matter model. According to Joseph Silk (Berkeley) the large-scale

Cold Dark Matter

An inflationary universe dominated by cold dark matter represents a minimal set of assumptions:

- ▶ Mass of the universe is dominated by non-baryonic matter
- ▶ Non-baryonic matter has negligible pressure (that is, no primordial velocity dispersion)
- ▶ Fluctuations in the mass distribution in the early universe originated in a random Gaussian process.

The power spectrum of the random Gaussian process is proportional to the wavenumber k. This gives only logarithmically divergent perturbations in space curvature; there is equal power per decade of wavelength in gravitational potential; and the spectrum of fluctuations continues to enormous lengths without cutoff.

Weakly interacting dark-matter particles—such as axions (almost massless Nambu–Goldstone bosons), photinos, higgsinos and quark nuggets—are expected to have negligible random motions: Thus the dark matter is cold. As the universe expands, the baryons dissipate energy by radiation and sink into gravitational potential wells provided by dark matter. Nick Kaiser (Institute of Astronomy, Cambridge, UK) introduced a biasing hypothesis of galaxy formation where galaxies form only above a critical threshold at the rare peaks in the initial random Gaussian spectrum of density fluctuations. (See A. Dekel, M. J. Rees, Nature **326**, 455, 1987; J. M. Bardeen, J. R. Bond, N. Kaiser, A. Szalay, Astrophys. J. **304**, 15, 1986.)

Simon White (University of Arizona), George Efstathiou (Institute of Astronomy, Cambridge, UK), Carlos Frenk (University of Durham, UK) and Marc Davis (Berkeley) are using high-resolution N-body techniques to study the CDM model (see Astrophys. J. **313**, 505, 1987). With a cosmological density parameter Ω equal to 1 from inflation, the model has only two adjustable parameters: the amplitude of initial perturbations and the Hubble constant (a value of 50 km/sec/Mpc is currently preferred). The amplitude of initial perturbations is adjusted to give the known clustering at present. With no free parameters left, the CDM model yields: correct galaxy counts as a function of potential well depth, flat galaxy rotation curves with the observed 150–250 km/sec amplitude, correct galaxy spin properties, correct power-law fit to galaxy correlation functions, observed small-scale velocity field, observed filaments and voids, correct counts for Abell clusters. Also galaxies with potential well depth of 200 km/sec are naturally biased relative to the matter to reconcile the value of Ω with the observed galaxy clustering. The model predicts strong evolution even at a redshift z of 1 and is consistent with evolution in number counts of quasars and radio galaxies.

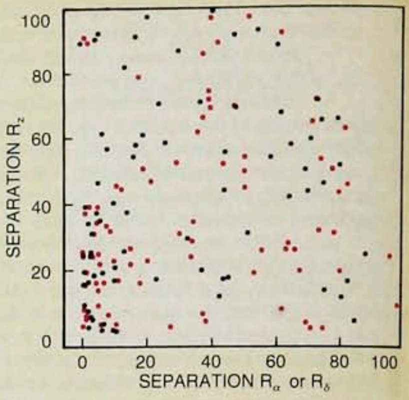
The model's failings are on the large-scale: neither the observed cluster–cluster correlation nor the reported values of large-scale cosmic drift can be produced.

cosmic drift measurements (if gravitationally driven) are expected to result in minimal temperature fluctuations $\Delta T/T$ of precisely this order (10^{-5}). "If they are truly measuring anisotropy in the microwave background," David Wilkinson (Princeton) tells us, "the Tenerife results are very significant."

Recently I. A. Strukov, D. P. Skulachev and A. A. Klypin (Space Research Institute, Moscow) from space observations with the RELICT experiment have set upper limits on fluctuations of 3 parts in 10^5 at angular separations of 90° (in quadrupole) and 4.5 parts in 10^5 at 20°. "Even if one throws out the standard initial spectrum of density fluctuations by assuming scale invariance is broken during inflation," says Bond, "It is hard to make the recent Soviet results compatible with large-scale streaming and the cluster–cluster correlation function."

Correlation functions. Independent evidence for large-scale structure comes from studies of the tendency of clusters of galaxies to cluster, which can be statistically described by a cluster–cluster correlation function. The 2-point correlation function $\xi(r)$ measures the deviation from a Poisson distribution for a pair of objects separated by a distance r. Neta Bahcall (Space Telescope Science Institute) and Raymond Soneira (AT&T Bell Labs)—and independently Klypin and A. I. Kopylov—have shown[2] that rich clusters are strongly correlated in space up to scales of 50–100 Mpc (megaparsecs). Such large-scale structures are difficult to form under some models (such as cold dark matter), but are consistent with the reports of large streaming velocities. "If Bahcall's results are correct, then they are completely inconsistent with cold dark matter, or with *any* plausible theory based on the inflationary paradigm for density fluctuations," Bond tells us.

The cluster–galaxy correlation function measures the way galaxies themselves cluster around clusters. Ten years ago James Peebles and Michael Seldner (both Princeton) found significant clustering out to about 80 Mpc (assuming $H_0 = 50$ km/sec/Mpc: quoted distances are halved if H_0 is doubled). This result conflicts with cold dark matter models that have difficulty yielding large-scale structure larger than about 30 Mpc. But Per Lilje and George Efstathiou (both Institute of Astronomy, Cambridge, UK) in a reanalysis find they cannot say anything reliable with this method beyond 40 Mpc. The galaxies do not seem to be as strongly clustered about clusters as Peebles thought earlier. Thus with not as much power in the correlation function at large scales the cluster–galaxy correlation function may be compatible with cold dark matter after all.



'Finger-of-God' effect in the distribution of clusters of galaxies as observed by Neta Bahcall, Raymond Soneira and William Burgett. Cluster pair separations in megaparsecs in redshift direction (R_z) are plotted versus the projected separation on the sky in right ascension (R_α, red) and in declination (R_δ, black). The elongation in redshift direction is apparent in both plots.

The galaxy–galaxy correlation function, studied by Peebles and Edward Groth (Princeton), measures the way galaxies cluster. They found that the correlation function dips down beyond 20–30 Mpc and does not indicate significant clustering of galaxies at greater scales. Peebles warns, "The 2-point correlation is a limited statistic; the correlation can be zero even with clustering." There would need to be a significant rise in the galaxy–galaxy correlation to show up in the cluster–cluster correlation function. Bond and Hugh Couchman (Canadian Institute for Theoretical Astrophysics) find the galaxy–galaxy correlation function for the cold dark matter theory is consistent with the Peebles and Groth observations. The cold dark matter model does not work with the observed clustering described by the cluster–cluster correlation function, but it does work with the galaxy–galaxy correlation function.

Cosmologists have had reservations about George Abell's catalog of clusters, identified from the Palomar Sky Survey. Efstathiou and Steve Maddox (Institute of Astronomy, Cambridge, UK) have a project under way involving more objective electronic counting of some six million galaxies in the southern hemisphere.

Bahcall has tested for selection effects in Abell's catalog. Other catalogs (the Zwicky and Shectman catalogs, for example) yield consistent results for the correlation function. Another test is to check for consistency of the correlation function for clusters projected on the sky and in depth from redshifts. "The correlation function is so strong that the main effect cannot come from a selection effect," Bahcall tells us. Completeness in the catalogs is better for the nearby statistical sample than for more distant objects. Bahcall estimates the nearby sample is at least 70% complete based on checking the one-to-one correspondence between Abell clusters and x-ray observations that detect gas within rich clusters.

Large-scale streaming motions. Bahcall has also reported evidence for large motions within big superclusters. One does not find the expected symmetric distribution in a plot of the separations of cluster pairs in redshift direction and as projected in the plane of the sky. Instead Bahcall, Soneira and William Burgett (Johns Hopkins) find a distribution stretched out in the redshift direction, like a finger of God pointing into the depth of the universe (see the figure on page 20). "This phenomenon suggests large cluster motions, about 1000 km/sec, but elongated structures that happen to be tilted toward our line of sight should also be investigated," cautions Bahcall.

Streaming observations may not be probing structure on as large scales as thought initially, according to Nick Kaiser (Institute of Astronomy, Cambridge, UK). The primary reason is that the distance estimates have larger errors at greater distances and the fitting procedures give very little weight to these. Also it is not a spherical region that is probed by the observations, contrary to what is usually assumed in the modeling.

At first the observations of streaming were thought to be a very good probe of the amplitudes of long-wavelength density fluctuations, which would still be evolving according to linear perturbation theory. The observations would then be a relatively direct probe of the conditions early in the universe. But if very massive collapsed objects are involved, then the density fluctuations must have been coupled in a nonlinear manner to each other. The observations are then a much more complicated probe of the primordial density spectrum, requiring more extensive N-body simulations than have so far been undertaken. And to make a "great attractor" regions of about 120 Mpc diameter would have to collapse, requiring larger amplitudes on large scales for density fluctuations than predicted by cold dark matter theory.

"It is difficult to make a scale-invariant spectrum work with large-scale streaming," Bond says. One solution is to break the scale invariance of the initial fluctuation spectrum and increase the amount of fluctuation on large scales. This appears quite difficult to do naturally in inflationary scenarios. Another possibility is having non-Gaussian initial fluctuations. "Within inflation, no one has come up with a source for non-Gaussian fluctuations," Peebles tells us, "but even they won't save the cold dark matter model."

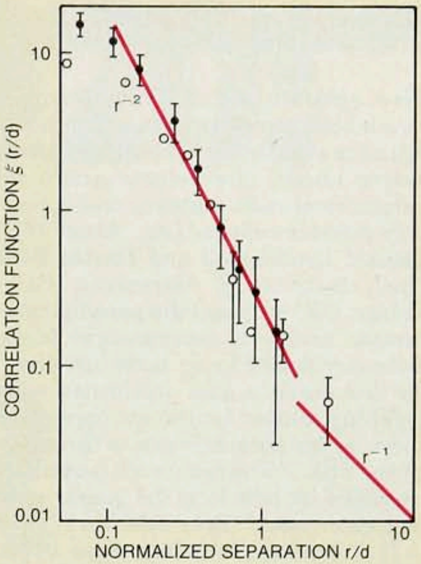
Some like it hot. "Hot dark matter models (with massive neutrinos) or those involving decaying particles could give flows of order 400 km/sec on the required very large scales," Adrian Melott (University of Kansas) tells us. Such models have not been popular in the West; they are associated with the Soviet school of Yakov Zel'dovich and A. G. Doroshkevich. In these models superclusters would be made in a "top-down" scenario *before* the galaxies. "The sequence of events is wrong," Peebles says. "We are in an old galaxy, in a young supercluster."

Peebles has argued for giving up "flat" universe models (see PHYSICS TODAY, May, page 17) favored by inflationary cosmology in favor of open-universe models. The parameter Ω that gives a measure of the overall curvature is 1 for a flat (Minkowski space-time) Einstein-de Sitter universe; it is less than 1 for an open universe. In these models the size of the horizon (that is, the length scale associated with the "turnover" in the fluctuation power spectrum) is proportional to $1/\Omega$ when matter is dominant. Peebles favors a baryon-dominated universe (without spatial curvature) with initial fluctuations in entropy because he claims it can produce both the Tenerife observations and large-scale velocity fields.[3]

And from the "great attractor" study Alan Dressler (Mount Wilson and Las Campanas Observatories) has determined Ω to be 0.13 ± 0.06.

Silk and Nicola Vittorio (University of Rome) have recently shown that an inflationary model can be constructed with low Ω by introduction of a nonzero cosmological constant Λ. Such a model (first proposed by Peebles), combined with hot dark matter scenarios, allows considerably more large-scale structure than do cold dark matter models.[4]

Cosmic string models by Neil Turok[5] (Imperial College, London, UK) show excellent agreement with Bahcall's cluster-cluster correlation. (See the figure on this page.) Cosmic strings can produce large-scale velocity fields, but perhaps not enough. Also cosmic strings would not give large-scale microwave background fluctuations. Melott and Robert Scherrer (Harvard-Smithsonian Center for Astrophysics) claim that cosmic string models can produce neither the correct cluster correlations nor large-scale streaming.[6]



Cosmic-string simulations by Neil Turok (filled circles) provide a good fit to the Bahcall-Soneira cluster-cluster correlation function (open circles) that measures the clustering of clusters of galaxies. Both are plotted in a dimensionless form (separation r is normalized to the sample's mean separation d) reflecting scale-invariance in the observed correlation.

Systematic comparisons of various theories are in progress,[7] but scenarios for galaxy formation seem elusive for the time being, at least using a minimal set of assumptions coming out of the Big Bang. A possibility is to consider models with nongravitational forces: "If it isn't superconducting cosmic strings," Ostriker tells us, "it is likely to be something as bad—or worse."[8]

—PER H. ANDERSEN

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