The Large-Scale Structure of the Universe

A second article on particle physics in the early universe looks at cosmic organization; next: supergravity

To begin with, there is structure: the universe is obviously and grossly inhomogeneous. Matter is progressively clumped into stars, galaxies, clusters of galaxies, and superclusters of clusters; ultimately it extends into a vast network of filaments, knots, and voids known collectively as the large-scale structure of the universe. It is not a particularly regular network, but then it is not exactly random, either. It is hard to understand how gravity alone could have produced it.

Next, on somewhat larger scales there is a sudden transition to uniformity. Taken a billion light-years at a time, the galaxies average out to a thin, featureless haze that drifts along with the cosmic expansion like windblown smoke. The only structural question is one of geometry: Is this homogeneous expanse closed and finite like a sphere, or open and infinite like a mathematical plane? No one knows. Neither does anyone understand the odd juxtaposition of uniformity and structure.

Finally, there is . . . something else. The universe may not even care what the galaxies are doing. Its dominant form of matter appears to be a mysterious ectoplasm that surrounds and pervades the galaxies and makes itself known only through gravitation. Astronomers refer to it as the "missing mass." It is utterly invisible, and no one knows what it is.

Three facts, three mysteries, three interlocking pieces of a single puzzle: How did the universe come to be organized in the way that it is? This is by no means a question for specialists. Most cosmologists now believe that the large-scale structure is in some sense a relic of the Big Bang, preserving on a billion-light-year scale the imprint of particle interactions at 10^{-35} second and 10^{-30} centimeter. During the last few years, in fact, some of the most avid researchers in cosmology have been the particle physicists; the large-scale universe seems to be the best place to search for exotica such as primordial black holes, massive neutrinos, or supersymmetric gravitinos.

For most of its history, however, the study of the large-scale structure has been a remarkably quiet endeavor—not so much a series of dramatic discoveries as a process of gradually dawning awareness. People have been talking about clustering since the 1920's, when the spiral nebulae were first recognized as external galaxies. Donald Shane and Carl Wirtanen at Lick Observatory began their famous million-galaxy survey in the 1950's. The closest thing to a breakthrough, in fact, came only in 1977, when P. James E. Peebles and his colleagues at Princeton University converted the Shane-Wirtanen survey into a two-dimensional map of the sky.

"One Million Galaxies" has been as popular as a poster as it has been in scientific journals. Probably the most striking thing about it is how *many* galaxies there are. But hardly less striking is the way that dense knots and clusters seem to link into a subtle network of filaments and voids.

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Now, Peebles himself was (and is) a skeptic about this network. "I'm a conservative," he says. "The human eye can see 'patterns' in random dots." But he is increasingly alone in that opinion. Filaments fit in well with the popular "Pancake" model of the large-scale structure, discussed below. New statistical tests have begun to verify their existence objectively. And most importantly, the filaments have begun to show up in three dimensions. Even as Peebles was publishing the Shane-Wirtanen map, in fact, the Estonian astronomer Jan Einasto was announcing his own evidence for filaments and voids: lumps and gaps in his sampling of galaxies at very large redshift.

Einasto was a pioneer in what has since become a minor industry. Redshift surveys, says Peebles, are certainly the most significant observational development of the last few years. The only real way to understand the large-scale structure is to see it in three dimensions, and the only way to get the third dimension is to use Hubble's law, which relates the distance of a galaxy to the redshift in its spectrum produced by cosmic expansion.

Einasto started out in the 1970's by focusing on a few very small regions of the sky, rather like a geologist taking a core sample. (In 1981 a similar core-sampling approach revealed the enormous "Hole in Space," a 200-million light-year void centered on a point some 500 million light-years beyond the constellation of Bootes the Shepherd (*Science*, 27 November 1981, p. 1016). More recently, observers have started to compile redshifts wholesale, using new digital detectors that can count individual photons and send the results directly to a computer. It is less like core sampling than strip-mining.

A prime example of this kind of work is the survey completed 2 years ago at the Harvard-Smithsonian Center for Astrophysics under Marc Davis, who is now at the University of California, Berkeley. The survey includes 2400 galaxies brighter than magnitude 14.5, which corresponds to a depth of roughly 400 million light-years. The sample has been subjected to much sophisticated analysis, but Davis's favorite display is still a three-dimensional model made by a Cambridge high school student. Each galaxy in the survey is represented by a pith ball on a string. The clusters, the filaments, and especially the voids stand out clearly. "I think we now have sufficient data to convince everybody that there is a loose, filamentary structure," says Davis. The problem is to figure out what made that structure.

Perhaps it was the missing mass. In 1933 the late Fritz Zwicky pointed out that the galaxies of the Coma cluster are moving too fast: there is not enough visible mass in the galaxies to bind the cluster together by gravity. Subsequent observations verified this "missing" mass in other clusters. And in the 1970's, as computers, image intensifiers, and other advanced instrumentation began to give observers a more detailed look at motions in individual galaxies, the same thing began to show up there. Both spiral and elliptical galaxies appear to be surrounded by broad, invisible halos. What is it?

The most conservative idea is that the galaxy is somehow shrouded in clouds of dim, low-mass stars, otherwise known as "brown dwarves." But there would have to be an awful lot of them. Where would they come from? And why should these stars be the only ones in the halo?

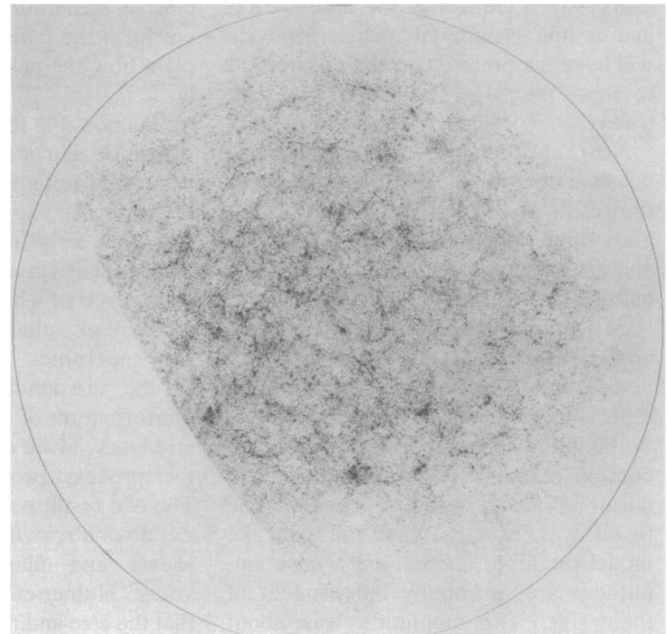
A halo of black holes would certainly be invisible, but again, where would they come from? Not from dying stars; a star that forms a black hole in the process of going supernova would inject most of its matter back into space, where it would hardly be invisible. The Big Bang? If the early universe had been chaotic enough to make black holes, those holes would have ended up swallowing virtually everything. Clearly, that did not happen.

Probably the most popular candidates for the missing mass now come from particle physics. For example, in 1980, physicists in the United States and in the Soviet Union announced independent evidence that neutrinos have a small mass, on the order of a few electron volts. The evidence is still quite controversial, but cosmologists have taken to the idea enthusiastically. Massive neutrinos produced in the Big Bang would be abundant (about 150 per cubic centimeter); they would be moving slowly enough to be trapped in massive halos around the galaxies (a few hundred kilometers per second); they would interact very weakly with ordinary matter; and in fact they would be utterly invisible. Altogether, they are exactly what one wants for the missing mass—if, of course, the neutrino mass is real.

Meanwhile, massive neutrinos have been given a starring role in what is currently the most popular theory of the large-scale structure: the "Pancake" model originated by Ya.B. Zel'dovich of the Institute of Applied Mathematics in Moscow in the early 1970's.

Essentially, Zel'dovich argues that the clusters came first, and the galaxies only formed later. In the aftermath of the Big Bang, he says, random motions in the primordial gas caused the gas to pile up in certain regions and become rarefied in others. Shock waves in the denser gas then forced it to radiate away its kinetic energy. The clumps thus stabilized, and as they cooled, the gas (somehow) began to form galaxies.

Now, spherical collapse is unlikely, Zel'dovich argues. In fact, the most likely shape for an initial clump is a flat sheet—a "pancake." Recently, he and his colleagues have refined this analysis to show that the highest densities actually occur along lines and points. It is appealing to identify these with filaments and the big clusters such as Virgo.



One Million Galaxies

The Shane–Wirtanen Survey shows a vast network of clusters, filaments, and voids.

In the original formulation, however, Zel'dovich faced the same problem that has bedeviled every model of the large-scale structure. Initially the universe was very uniform: the 2.7 K cosmic background radiation, emitted from the cooling cosmic plasma about 100,000 years after the Big Bang, shows fluctuations of less than one part in 10,000. On the other hand, the galaxies are very old: from spectroscopic evidence, the most ancient globular clusters in the Milky Way seem to rival the age of the universe. The galaxies probably began to form within a billion years of the Big Bang. Yet how could the universe have gone from homogeneous plasma to pancakes to galaxies so quickly? Gravity alone was simply not strong enough to do it.

This conundrum does have a partial resolution, however, if neutrinos have mass. In 1980, Zel'dovich and his coworkers pointed out that the weakly interacting neutrinos would have decoupled from the Big Bang plasma long before other particles. Then as they cooled, their mass would have allowed gravity to start pulling them into clumps. Ordinary matter, meanwhile, would stay hot and uniform until the cosmic background photons were radiated at 100,000 years—whereupon the cooling matter would quickly fall in with the older clumps of neutrinos to form protoclusters.

For reasonable values of the neutrino mass, Zel'dovich and his followers have estimated that these primordial clumps would have a typical size of 100 million light years, and a typical mass of 10^{15} solar masses. This is about right for a supercluster. Moreover, it appears that neutrinos trapped around a contracting protogalaxy would form a halo of about the right mass.

Unfortunately, the resolution is only partial. The model predicts that the galaxies are relatively young, forming well after the protoclusters, whereas the galaxies are actually very old.

Indeed, some would argue that it is the clusters that are young. "If the clusters formed first, then why aren't all galaxies stuck in clusters?" asks Peebles. "Most galaxies are like ours—on the outskirts, in loose groupings, just starting to fall in."

"I've become convinced that the pancake picture won't fly," he says, although he admits that he has attracted very few disciples to his cause. Almost alone, he continues to champion the more conservative hierarchical model, which postulates that the galaxies came first and were then pulled by gravity into a hierarchy of clusters.

This model does have the advantage of being very concrete. For example, Peebles has been able to derive a successful statistical relation between mass and the rotational motions in galaxies, clusters, and superclusters. On the other hand, as Peebles is the first to admit, the hierarchical model rests on utterly ad hoc assumptions about density perturbations in the aftermath of the Big Bang. One simply assumes that matter will form galaxy-sized clumps in the early years, just as one assumes that those galaxies will have the precise correlations needed to form the large-scale structure seen today.

Now, until recently that was all right, because the initial perturbations were the result of Big Bang physics that nobody understood. Besides, Zel'dovich and his followers needed ad hoc perturbations too. But particle physicists have been working hard to apply their grand unified theories to the very early universe, and last summer, for the first time, they were able to make predictions of the initial density perturbations in the context of the "New Inflationary Scenario" (*Science*, 28 January, p. 375). The result was exactly what the pancake model required: fluctuations whose amplitudes are essentially independent of their size. The amplitude was about 100,000 times too large—unfortunately—it grossly violates the limits set by the uniformity of the microwave background—but that was only in the simplest grand unified theory. Other versions do better. The particle theorists are optimistic that they are on the right track, and most, in fact, seem to be enthusiasts for the pancake model.

The pancake model is clearly the most elegant and comprehensive model we have for the large-scale structure, and its popularity is well deserved. But just as clearly, something is missing. In its present form the pancake model cannot explain how the galaxies formed so quickly.

One possible fix, recently explored by Princeton astronomers Jeremiah P. Ostriker and Lennox L. Cowie, is the role of primordial explosions. They postulate that the early universe brought forth small stellar systems containing massive stars, each of which quickly ran through its cycle of stellar evolution and erupted as a supernova. Shock waves sweeping up the surrounding gas then triggered the formation of galaxies and new massive stars. More explosions ensued, and the process proceeded exponentially. The end result was a universe much like Zel'dovich's, with galaxies arrayed in sheets and filaments around empty voids. Numerical calculations indicate that the size and mass of these structures would be very near to what is observed. But of course, the model still begs the question of where the initial density fluctuations came from.

Another possibility, increasingly popular, lies with the particle physicists' theories of supersymmetric gravity. Among the many predictions of supergravity is the existence of a particle known as the gravitino, a kind of skewed mirror image of the ordinary gravitational field. Gravitinos produced in the Big Bang would begin forming clumps very early, just as the massive neutrinos do in Zel'dovich's model. But the detailed interactions and masses would be different, and in particular, it turns out that a gravitino could easily have a mass of about 1000 electron volts without violating the constraints on the cosmic mass density. And at 1000 electron volts, the typical minimum mass of a gravitino clump would be about the mass of a typical galaxy, which means in turn that ordinary matter falling into the clumps would make galaxies as well as superclusters—if, of course, gravitinos are real.

The problem of the large-scale structure was a long time building. But over the last 10 years, and particularly over the last 2 or 3 years, advances in observation and theory have brought it to the forefront of cosmological research. In 1985, moreover, the Space Telescope should start bringing the problem a great deal closer to resolution by pushing the redshift surveys deep enough to see the structures evolving with time, or to pin down when the galaxies did form.

"Most of the time," says Peebles, "we work in narrow fields, scratching at the small problems. But we do so in the hope that a pattern will emerge to tell us something global and fundamental. What is the universe like, for instance? And where did it come from?"

—M. MITCHELL WALDROP

How Mammalian RNA Returns to Its Genome

Work with certain small nuclear RNA's is giving clues about the apparently common flow of information from RNA back to DNA

The copying of mammalian RNA transcripts into DNA and the subsequent integration of the complementary DNA (cDNA) back into the genome, a once "forbidden" route of information flow, is now a well-established phenomenon. Indeed, as much as 20 percent of some mammalian genomes may owe its existence to this little understood process. A series of recent studies on human genes and pseudogenes for certain small nuclear RNA's (snRNA's) is providing some insight into the many questions that surround reverse transcription in mammalian germ-line cells (*1*).

One of the most cogent pieces of evidence for the reverse flow of genetic information from RNA back into DNA in mammalian systems come from work carried out by Laurel Bernstein, Stephen Mount, and Alan Weiner at Yale University. These investigators find that human U3 snRNA can be reverse-transcribed in vitro by the avian myeloblastosis virus enzyme to yield a cDNA that corresponds in both length and sequence to four very similar human U3 snRNA pseudogenes. In separate studies, not yet published, there are also indications of reverse transcriptase–mediated pseudogene production in *Drosophila*. This work, by Richard Lifton in David Hogness's laboratory at Stanford University, shows that the process is more widespread in evolution than previously recognized.

Small nuclear RNA's are especially interesting because some of them appear to be involved in the processing of long nuclear precursor molecules of messenger RNA's and perhaps ribosomal RNA as well. This was the reason that Weiner began in 1979 to search for snRNA genes. However, when the Yale group screened libraries of human genomic DNA and used the relevant RNA molecules as probes, they managed to fish out nothing but pseudogenes, most of which were shown by DNA sequencing to be only one-third the length expected for intact genes.

These disappointing early results presaged a pattern of discoveries, and it is now clear that human snRNA genes and pseudogenes comprise a small hodgepodge of moderately repetitive sequences. In fact, pseudogenes for one of the snRNA's, U1, and possibly for other related RNA's, appear to outnumber the genes by a factor of 10.