Dark Matter, Structure, and Strings

In late July, about 150 astronomers gathered at the University of California, Santa Cruz, for a 2-week workshop on "Nearly Normal Galaxies." As the title suggests, the discussion was wide-ranging. Yet two issues stood out: dark matter and the large-scale structure. In itself this was hardly surprising, since these two issues have haunted extragalactic astronomy for nearly a decade. Indeed, they are central to an understanding of how galaxies formed. But some of the most dramatic findings have only been announced this year. Thus, the Santa Cruz workshop came at an especially opportune moment. In the following briefings, Research News draws on the workshop presentations to summarize astronomers' latest thinking on these subjects.

The Large-Scale Structure

As workshop organizer Sandra Faber pointed out, no one is surprised to find some sort of structure in the universe, simply because a completely homogeneous universe would be unstable. If the cosmic plasma came out of the Big Bang with even minor fluctuations in density—as it surely did—then gravity would have caused those fluctuations to grow inexorably; presumably, the densest clumps eventually formed into the stars and galaxies we see today.

But what *is* surprising is the sheer size of the structure, said Faber. The galaxies appear to trace out a vast network of bubbles, filaments, and voids on a scale of hundreds of millions of parsecs. (A parsec is 3.26 light-years.) The farther out the observations go, in fact, the larger the structures seem to be.

Nowhere has this finding been documented more vividly than in the "slice of the universe," which was first made public earlier this year by Valerie de Lapparent, Margaret Geller, and John Huchra of the Harvard-Smithsonian Center for Astrophysics, and which was reviewed at the workshop by Huchra.

The slice itself is a map of the galaxy distribution in a thin wedge 6 degrees thick, 117 degrees wide, and some 150 to 300 megaparsecs deep, Huchra explained. The distance to each galaxy was determined from its redshift by the Hubble law; in this particular slice there are nearly 1100 galaxies. The most prominent feature in the map, a dense clump of points that looks vaguely like a human figure, is the rich cluster of galaxies in the constellation of Coma Berenices. But the most intriguing feature, he said, is the way the galaxies outside the Coma cluster seem to trace out well-defined ridges, which in turn define the edges of surprisingly empty voids measuring 30 to 50 megaparsecs in diameter. The general impression is of taking a slice through soapsuds, with the galaxies lying on the bubble walls. In fact, the Coma cluster seems to lie at the intersection of several such bubbles.

Hints of this foamy structure have been seen in any number of earlier surveys, said Huchra. But in the past the maps have tended to be fragmentary, largely because redshifts have been so time-consuming to obtain. The Center for Astrophysics survey, by contrast, has been under way since the early 1980's using new techniques for obtaining lots of redshifts quickly. Ultimately, Huchra and his colleagues plan to obtain a complete sample of galaxies down to magnitude 15.5 over a large area of the sky; from that sample they then hope to map the large-scale structure unambiguously out to a distance of several hundred megaparsecs. In the meantime, Huchra was able to show workshop participants a second slice, recently completed, that covers a 6-degree segment of the sky lying just to the north of the first. This second slice has nothing to compare with the Coma cluster, of course. But it does show the same kind of sharply defined bubble walls, many of which seem to be continuations of the walls seen in the first slice. Moreover, in its extreme outer regions the second slice intersects the edge of the Boötes void, an enormous, 124-megaparsec gap in the galaxy distribution first discovered in 1981. The void is clearly visible. More slices will be forthcoming, Huchra said.

Another recent discovery discussed at the workshop—indeed, probably the most startling and controversial issue of the entire 2 weeks—was the large-scale streaming motion, which was announced earlier this year by a group of astronomers who quickly became known to their colleagues as "The Seven Samurai."*

The streaming motion was found serendipitously, explained team member Alan Dressler of the Mount Wilson and Las Campanas Observatories. He and his colleagues were actually engaged in a 5-year survey designed to improve the calibration of distances to elliptical galaxies. However, when they plotted the redshifts of bright ellipticals over a 100-megaparsec region around the Milky Way—a region that takes in a number of superclusters—they found a pattern of large random velocities superimposed on the overall Hubble recession. Indeed, the velocity pattern showed lots of shear, with neighboring patches of galaxies often moving in opposite directions at hundreds of kilometers per second.

More important, however, the seven astronomers found that the average velocity of the galaxies in this 100-megaparsec region is comparatively small relative to the Milky Way—which is astonishing, because the Milky Way itself is known to be moving at some 600 kilometers per second relative to the 2.7 K cosmic background radiation. So if the average velocity of this 100-megaparsec neighborhood is small relative to us, then all these other galaxies must also be moving at some 600 kilometers per second relative to the background. In fact, they seem to be moving as a unit.

Another intriguing fact: in the course of their survey the astronomers noticed that the majority of their galaxies lie roughly in a plane, perhaps analogous to one of the bubble walls discussed by Huchra. The streaming motion is directed within the plane, rather as if the galaxies were pegged to a plate sliding sidewise on a table. Moreover, the motion is in the general direction of the Hydra-Centaurus supercluster, which is relatively nearby as superclusters go. However, Hydra-Centaurus shares the streaming motion—in fact it is moving faster than any other patch of galaxies in the region—and there is nothing obvious on the other side that could be pulling it.

There is certainly room for skepticism about these results, especially since it is hard to imagine what could have gotten so much mass moving so rapidly. Indeed, as discussed below, the streaming motion seems inconsistent with the most successful dynamical models of the large-scale structure. On the other hand, the findings of the Seven Samurai were not entirely unexpected. Hints of large-scale streaming motions have been seen in earlier surveys, for example. At the workshop, moreover, Neta Bahcall of the Space Telescope Science Institute in Baltimore told participants that she and her

*David Burstein, Arizona State University; Roger L. Davies, Kitt Peak National Observatories; Alan Dressler, Mt. Wilson and Las Campanas Observatories; Sandra M. Faber, Lick Observatory; Donald Lynden-Bell, Cambridge University; Roberto Terlevich, Royal Greenwich Observatory; Gary Wegner, Dartmouth College.

colleagues have done a statistical analysis on pairs of clusters and found root-mean-square velocity differences on the order of 2000 kilometers per second—roughly three times larger than the Seven Samurai result.

Whatever one thinks of the streaming motions, however—for the moment, most astronomers seem to be taking a wait-and-see attitude—there still remains the frothy, large-scale structure itself. It is far from random. It cries out for an explanation. Thus, astronomers are inexorably led to the other half of the equation: dark matter.

The Cold Dark Matter Model

There is now a broad consensus among astronomers that the dark matter does exist. Indeed, it seems to be the dominant form of matter in the universe. In essence, the argument is that the spiral galaxies rotate too fast and the galaxies in clusters move too fast; the visible stars simply do not contain enough mass to hold these systems together by gravity. So something else must be making up the deficit, some kind of cosmic ectoplasm that permeates the galaxies, that has enormous mass, and that is utterly invisible. In short, dark matter.

Whatever this stuff is, it is clearly the key to understanding the evolution of the large-scale structure. There is so much of it—roughly 90% of the mass in the universe, according to most estimates—that the ordinary "baryonic" matter in the visible galaxies is little more than flotsam, drifting along wherever the dark matter carries it.

The working hypothesis of most astronomers is that the dark matter consists of a haze of previously unknown elementary particles left over from the Big Bang, in much the same way that the photons of the 2.7 K background radiation are primordial relics. If these particles were to interact very weakly with ordinary matter, goes the argument, they would effectively be invisible; if each of them also had a tiny mass, then together they would have exactly the kind of gravitational effects observed.

The physicists have obligingly predicted a wide variety of such particles in their theories of grand unification and supersymmetry. (The dark matter candidates are generically known as weakly interacting, massive particles, or WIMP's.) Unfortunately, these theories are also rather vague about the masses and interaction strengths of the WIMP's, which means that firm cosmological predictions are out of the question. Thus, one popular approach among cosmologists is to work backward, using theoretical calculations and computer simulations to see what properties the WIMP's need in order to reproduce the observations. Just within the past year or two, in fact, that effort has converged on one very successful set of assumptions known as the cold dark matter model.

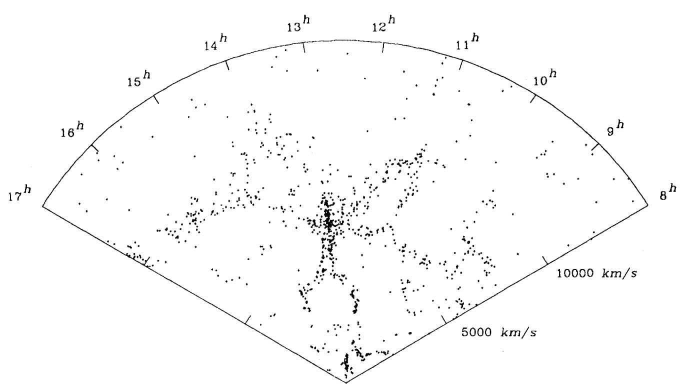
The WIMP's in this picture are "cold" in the sense that they came out of the Big Bang fireball at nonrelativistic velocities. Calculations show that there are several WIMP candidates that would have done just that, with the most notable being the so-called axions and photinos. But in any case, it turns out that the details of the WIMP's are almost irrelevant. Given that the dark matter was nonrelativistic at early times, gravity would have caused density fluctuations to grow in a certain, predictable way as the universe expanded. Thereafter, as the universe continued to expand and as the baryonic matter cooled off enough to undergo gravitational contraction, these dark matter clumps would have acted rather like cosmic potholes, pulling in the baryonic matter and trapping it. The upshot is that objects ranging from 10^8 to 10^{12} solar masses would have formed relatively quickly in a cold dark matter universe. And this is in fact what is observed: not only do virtually all galaxies fall within that mass range, but from spectroscopic evidence they are known to be essentially as old as the universe itself.

The cold dark matter picture thus provides an attractive explanation for the existence of galaxies. However, before the model can reproduce the observed clustering of galaxies, it needs one other ingredient: biasing.

As Avishai Dekel of the Weizmann Institute explained to the workshop, perhaps the most compelling rationale for biasing is the existence of very large voids such as the one in Boötes. The 2.7 K cosmic background radiation was emitted by the cooling plasma about 100,000 years after the Big Bang, he pointed out, and its striking uniformity shows that the material in the universe at that time was homogeneous to better than one part in 10^4. So if the voids really are empty, he said, then we cannot explain how they form. There seems to be no reasonable way for gravity, explosions, or anything else to have moved that much mass around within the lifetime of the universe. It is much more reasonable to say that the voids are actually filled with matter—both baryonic and dark—but for some reason the baryonic matter has not condensed into galaxies. Or, to put it another way, mass does not follow light; somehow, galaxies were formed only at the very highest peaks of the density fluctuations. Thus the term "biasing."

Biasing is actually an old idea that was revived in 1984 by Nicholas Kaiser of the University of California and James M. Bardeen of the University of Washington. And it does have a certain plausibility. Assuming that the first galaxies formed in the densest regions—as they almost certainly would have done—then it is easy to imagine any number of ways they could have disrupted the formation of galaxies elsewhere. Perhaps they heated the nearby gas with ultraviolet radiation, for example, or with supernova shock waves, and thus made it impossible for the material to condense.

But whatever the mechanism, biasing has the virtue of producing large-scale structure automatically, even if the original density perturbations were distributed at random: the galaxies form only in the densest regions, and the densest regions, like the highest peaks of a mountain range, tend to lie close together in ridges and clumps. Indeed, as Simon White of the University of Arizona explained at the workshop, recent numerical simulations show that a biased cold dark matter universe would form large-



A slice of the universe. *This three-dimensional map of 1061 galaxies, produced by astronomers at the Harvard-Smithsonian Center for Astrophysics, covers a strip of the northern sky stretching from Gemini on the right to Hercules on the left. The radial coordinate of each galaxy is its redshift, or recession velocity, which can be converted to its distance by the Hubble law. Random velocities among the galaxies tend to smear out the distributions in the radial direction; nonetheless, the pattern of bubbles and voids is striking.* [*Source: Harvard-Smithsonian Center for Astrophysics*] scale structures remarkably similar to the voids and sharp bubble walls discussed by Huchra. Furthermore, he said, with biasing parameters chosen to reproduce the observed galaxy distribution on smaller scales, he and his colleagues† have been able to reproduce many of the quantitative measures of the large-scale structure. Their model clusters have masses and luminosities typical of real clusters, for example, and their model galaxies have random velocities typical of real galaxies.

In addition, as White's co-worker Carlos Frenk of the University of Durham told the workshop, some preliminary results from the simulations indicate that biasing of the correct magnitude may arise quite naturally: in essence, cold dark matter tends to clump up much more strongly in regions of greater than average density, and much less strongly in regions of less than average density.

However, it must be said that the biased cold dark matter model has run into two serious problems with observation. First, the numerical simulations produce nothing resembling the large-scale streaming motions discussed by Dressler; moreover, the average relative velocity between simulated cluster pairs is much smaller than the 2000 kilometers per second quoted by Bahcall. Second, the simulations produce clusters that have a much lower spatial correlation than real clusters. Bahcall and her colleague Raymond Soneira have analyzed the catalogue of rich clusters compiled in the 1950's by George Abell of the University of California, Los Angeles, and have found a strong statistical correlation on a scale of roughly 100 to 200 megaparsecs. In the simulations the scale is less than half that value.

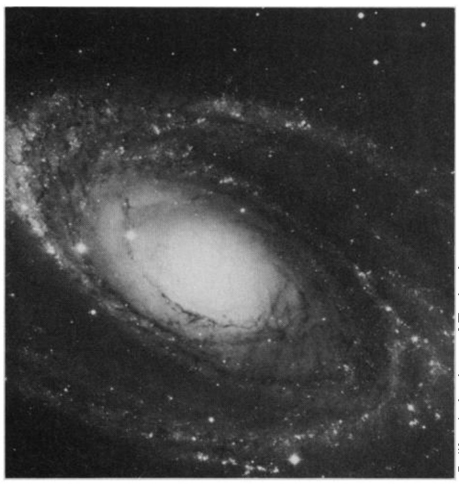
Of course, these very observations are also among the most problematic and controversial results presented at the workshop. For example, the Abell catalogue is rife with selection effects, as Abell himself was the first to acknowledge. (He identified his clusters by scanning the plates of the Palomar sky survey, which is known to be far from perfect.) So one can safely say that the jury is still out.

On the other hand, the discrepancies are sufficiently striking that many theorists feel called upon to explain them, either by adding something to cold dark matter or by abandoning the picture completely. Perhaps the most intriguing new approach—or the most outrageous, depending on one's point of view—is the idea of cosmic strings.

†Simon D. M. White, University of Arizona; Carlos S. Frenk, University of Durham, Durham, United Kingdom; Marc Davis, University of California, Berkeley; George Efstathiou, Institute of Astronomy, Cambridge, United Kingdom.

Cosmic Strings?

Cosmic strings have been predicted in a number of elementary particle theories, including the recently proposed theory of superstrings. (Despite the confusion of names, however, cosmic string and superstring are very different objects.) Cosmic strings would be infinitesimally thin threads of energy, about 10^{-30} centimeters thick. They would also be enormously massive, about 10^{22} grams per centimeter, and exceedingly taut, with about 10^{42} dynes of tension. Like the WIMP's themselves, they would have been produced abundantly in the Big Bang. Indeed, they would have started out as a dense network of lines and loops whipping through the universe at close to the speed of light. Then, as the universe expanded, the big loops would have shed smaller loops, while the smaller loops would have radiated away their energy in the form of gravity waves; by now only a few of the very longest strings would be left, winding from one end of the observable universe to the other.


California Institute of Technology

Flotsam in the dark matter. *Spiral galaxies such as this one, M81 in Ursa Major, rotate much too fast. Especially in the outer regions, there is not enough mass in the visible stars to hold the system together by gravity. Some kind of cosmic ectoplasm—the dark matter—must be making up the deficit.*

Meanwhile, of course, the cosmic strings would have produced noticeable gravitational effects in the primordial gas and dark matter. In the wake of a long string, for example, the material would have formed a flat sheet of higher than average density. In the wake of a loop, it would have formed an elongated, cigar-shaped enhancement. As the universe evolved, the cold dark matter presumably would have enhanced those density fluctuations even further according to the model discussed above. In other words, the cosmic strings would have generated the "seeds" for galaxies and larger structures.

The intriguing thing about all this, as Neil Turok of Imperial College explained to workshop participants, is that one can calculate the average rate at which loops of various sizes will split off from larger loops, together with the amount of dark matter that each size loop will attract. The answer depends upon a dimensionless number that is related to the mass per unit length of the string; indeed, that number is the only free parameter in string theory. If one then demands that the results match the observed distribution of galaxies and clusters, he said, one can estimate the value of the parameter in several independent ways. In each case it comes out to be about 10^{-6}—which also happens to be precisely the magnitude predicted in particle theories. Thus, he said, cosmic string theory is remarkably consistent with observation.

In addition, said Turok, numerical simulations show that the statistical correlation function between large loops is virtually an exact fit to the correlation function that Bahcall and Soneira found for Abell clusters. This is an especially stringent test for the cosmic string picture, he pointed out, because the correlation function is a purely geometric quantity that is independent of the string theory parameter. For that matter, it is also independent of the overall matter density of the universe and the Hubble constant.

No one knows yet whether cosmic strings could have produced large-scale streaming motions of the magnitude observed by the Seven Samurai. Nonetheless, astronomers are taking the sting model very seriously indeed. Earlier this year there was even a brief flurry of excitement when it seemed that two widely separated quasars might actually be two different images of the *same* quasar, with the images split by the gravitational field of an intervening length of string. While subsequent observations have made this gravitational lens interpretation seem much less likely—the two quasars in question do have the same redshift, but their spectra have turned out to be not quite as similar as people first thought—researchers continue an eager watch for observational evidence of cosmic string. ■

M. Mitchell Waldrop

ADDITIONAL READING

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