The Life History of Galaxy Clusters

Astronomers are watching the formation of large-scale structures in the universe by observing the early years of clusters of galaxies; they are also finding more of these early clusters than theories predict

In the universe's family of structures, clusters of galaxies are the overlooked middle child. The littlest structures in the family are single galaxies; the biggest are sheets and filaments of millions of galaxies, with names like the Great Wall and Perseus-Pisces. As usual, the littlest and biggest get all the attention: Observers map them to the largest scales and earliest times, theorists fret about when they were born and how they developed since. The middle children have been largely neglected. Observers have named and mapped nearby clusters, which are typically giant balls of thousands of galaxies a few million light-years across. But only recently have they begun to study more distant clusters to fill in the early years of the middle child.

NASA

Mature cluster. X-ray image of a cluster called Abell 2256 taken with the German-U.S. ROSAT satellite. Hot gases are concentrated in the center of the cluster; they tend to be dispersed in clumps in earlier clusters. Asymmetry in this image suggests that two separate clusters may have merged together in Abell 2256.

Already they are finding, as James Gunn of Princeton puts it, that clusters "do evolve. They're different beasts earlier." And that life history is interesting not just on its own but because it is providing the earliest and least ambiguous evidence for one of cosmology's big questions: How does structure form? So far, studies of distant—and therefore young—clusters neatly fit the conventional picture of how matter was sculpted into structures on all scales in the early universe. This simple, pretty scenario predicts that when the newly born universe had slowed its expansion and cooled enough to form gases, gravity collected the gases into galaxies. Galaxies popped out all over, preferentially in sheets. Where sheets intersected, gravity pulled galaxies into filaments; and where filaments intersected, galaxies knotted up into clusters.

But the new observations have also presented theorists with a problem: Distant clusters are found in such high numbers that they threaten received wisdom on another of cosmology's big questions: How will the universe end? If the numbers are to be believed, the universe is not only flying apart much more rapidly than cosmologists have been predicting, it is fated to go on expanding forever.

The strategy for piecing together the formation of clusters is simple: Look at nearby clusters, look at more distant clusters and figure out what happened in between. Nearby clusters are orderly and, judging by the steady orbits of their galaxies, already mature. Their galaxies are usually ellipticals, gathered most tightly in the cluster's core. Distant clusters, in contrast, look like they've been caught in the act of forming. They are shapeless; their galaxies are messy-looking, rolling into the clusters' cores, spitting out hot gas, changing shape from fragile spirals to robust ellipticals and, compared to galaxies not in clusters, generally growing up faster. "Living inside a [distant] cluster," says August Evrard, a theorist at the University of Michigan, "is like living in a universe on fast forward."

This picture of cluster formation is emerging from a series of observations by international teams of astronomers using both ground-based telescopes and orbiting observatories. Several groups of x-ray astronomers using the German-U.S. x-ray satellite called ROSAT, for example, have so far found a few dozen distant clusters that are bright with gas at 10 to 100 million degrees Kelvin, hot enough to give off x-rays. Some of the hot gas is left over from the Big Bang; some has been manufactured by exploding stars. But on the whole, the gas seems brightest at the centers of these clusters, suggesting their cores have already formed. These clusters are up to 4 billion light-years away, at red shifts around 0.4 or 0.5.

Another team—Gunn, Richard Ellis, and Carlos Frenk from Durham University in England, and Alan Dressler from the Carnegie Observatories—looked at clusters even farther out, at red shifts of 0.75 and 0.9, and compared them to the nearer clusters. The distant clusters had nowhere near as much x-ray emitting gas. The gas, moreover, doesn't congregate at the centers of the clusters, but is clumped randomly: "[The clusters] look like two fried eggs," said Richard Mushotzky, a member of the ROSAT team at NASA's Goddard Space Flight Center, "or like pepperoni pizzas." The implication is that clusters, as they age, begin manufacturing intergalactic hot gas that clumps up, merges, and sinks to the core.

Still other observers find that galaxies also merge as clusters age. Earlier observations by Dressler, Gunn, August Oemler from Yale, and Harvey Butcher from the Netherlands Foundation for Research in Astronomy found that many of the galaxies in distant clusters, unlike the ellipticals in nearby clusters, were spiral galaxies with delicate, fragile disks that clearly had not yet done much merging. More recently, another team—Russell Lavery from the Carnegie Institution of Washington, Michael Pierce at the National Optical Astronomy Observatories, and Robert McClure from Canada's Dominion Astrophysical Observatory—spotted those delicate spirals in the process of transforming into ellipticals.

Using the Canada-France-Hawaii telescope, the group peered into two clusters at red shifts of 0.4. Half the galaxies had unusually close companions, some of which were pulling each other out of shape. "They're interacting with each other," said Pierce. "The implication is that they're relatively new arrivals into the cluster." Then the team looked at clusters at even larger red shifts of 0.7, and though the galaxies' shapes at this distance were unresolvable, the pairs

Peering at the Edge of the Universe

The most distant structures in the universe are galaxies and quasars, at red shifts ranging from 2.0 to 5.0, only a billion years after the Big Bang. By "structure," however, cosmologists usually mean not individual galaxies but clusterings: either discrete clusters or the faint, sprawling sheets of galaxies called walls and superclusters. Discrete clusters are seen at red shifts of 1.0 and above (see main story). Sheets are clearly visible nearby but are too faint to pick out far away. Recently, however, an international team of astronomers found not only sheet-like clustering at great distances, but they also found where such clustering, on average, begins.

To find faint sheets, Joe Silk of the University of California, Berkeley, Bruce Peterson at Australia's Mt. Stromlo Observatory, and Joe Wampler at the European Southern Observatory took pictures of the sky, then sliced the sky according to the brightness of the galaxies. One slice, for instance, held galaxies of 21st magnitude, about the average brightness of the night sky. The next slice held galaxies at 22nd magnitude, 2.5 times fainter, and so on to galaxies at 28th magnitude, 1000 times fainter than the average night sky. The assumption was that each fainter magnitude corresponded to a greater distance.

On each slice, the team used a statistical measure to calculate how clustered the galaxies were. Because gravity draws things together over time, nearby galaxies should cluster more than galaxies that are fainter, more distant, and further back in time. When Silk and his colleagues compared the amount of clustering in successively more distant slices, the clustering fell as expected. But at the 25th magnitude slice, which Silk says corresponds to a red shift of 1.0, clustering leveled out. The interpretation is fairly dramatic. "It would level out like that," said Silk, "if we're looking at the edge of the universe." Silk uses "edge" statistically: He and his colleagues count only fully formed galaxies, not high-red shift newborns like quasars and shapeless clouds condensing into stars, and they find the edge of the ordinary universe. At the edge, Silk said, "when you look fainter and fainter, you're not seeing [galaxies that are] deeper, only dimmer." Silk's survey also implies, he says, that the sheet-like clustering of these galaxies materializes about the same time, around a red shift of 1.0.

The observations are wobbly, however. The distances are all estimates, based on assumptions, and probably full of error. And confirming that the sheets really are sheets, and not random superpositions of galaxies at near and far distances, is a problem. "The clincher would be red shifts [of individual faint galaxies]," says Silk, but detectors for taking red shifts are sensitive only to 24th magnitude. "Until you get galaxy red shifts," agrees Marc Postman of the Space Telescope Science Institute, "it's still all a crap shoot."

–A.F.

they formed were even closer. Pierce thinks the pairs were merging into single objects. "At 0.4," he said, "we're seeing the tail end of a process that's much stronger at 0.7. [Between red shifts of 0.7 and 0.4], the cluster is still coming together."

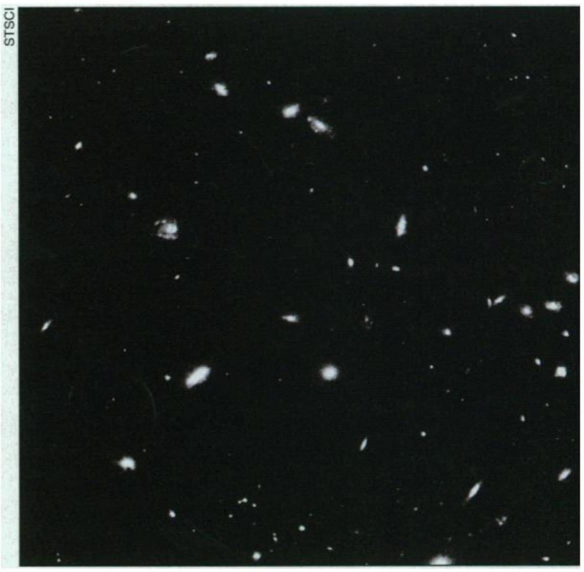
The observations seem to support a picture of clusters forming from the inside out: young spirals swirling together, maybe coalescing to form ellipticals, losing hot gas, and falling into a dense core where galaxies from the outskirts of the cluster eventually surround them. That's the scenario expected if, as theory holds, clusters form where great filaments of galaxies intersect. The timing of the process seems to be about right, too. The theories predict that, given the rate at which gravity would pull filaments into clusters, the cluster cores should be forming around a red shift of 1.0. Some observations, however, may be on the verge of showing clusters around a red shift of 1 that are already fully formed. But clusters, as Gunn says, "are by no means cut out with a cookie cutter." Observers still haven't found enough distant clusters to know what the majority looked like and when they formed.

Too many clusters

A much bigger problem for theory comes from the numbers of clusters observers are seeing at large distances. The number of clusters in the early universe will depend on how fast the universe expands, which depends on omega, a measure of the density of mass in the universe. A fast expansion—a low omega —means the universe will expand forever. A slow expansion and a high omega mean the expansion will reverse and the universe will close back down. The hairline balance between the two, an omega of 1.0, means the universe will continue expanding, but more and more slowly. Most theories of structure formation, together with the nearly impregnable version of the Big Bang called the inflationary theory, all firmly predict omega is 1.0. For theorists, it's the current best bet.

The observations, though, tell a different story. In 1986, Gunn, using a four-eyed camera he helped invent, began systematically surveying the sky at optical wavelengths for distant clusters. The survey should be published this year. So far, Gunn, along with Beverly Oke from Caltech, Donald Schneider from the Institute for Advanced Study, John Hoessel from the University of Wisconsin, and Jennifer Christensen and Marc Postman from the Space Telescope Science Institute (STScI), has mapped 250 clusters. The red shifts inferred from the clusters' brightness range out to 1.0, half the age of the universe.

At that red shift, says Postman, "the difference between a low- and high-omega universe should be apparent." A high-omega, slowly expanding universe at that point of its evolution would be relatively dense and its volume relatively small. Nascent clusters, trying to pull inward against dense surroundings, should find it harder to form, and observers should see relatively few clusters. At the same red shift, however, a low-omega, rapidly expanding universe would have a much lower density. So clusters would form more readily and observers should count more of them. (Observers trying to measure omega could just as well count galaxies, but each square degree holds 26,000 galaxies; counting clusters is easier.)



STSCI

Galaxy assortment. Image of a distant cluster (CL0939+4713) shows mixture of elliptical and young spiral galaxies typical of young clusters.

Specifying the exact number of clusters that theory predicts gets complicated, but the number that Gunn and his colleagues found is uncomfortably large for a universe with an omega as high as 1.0. The survey found 42 clusters per square degree and, because the process of finding clusters "isn't 100% foolproof," says Postman, "we know at the distant end, we're missing 20%." These numbers imply that omega is low, the best theories are wrong, and the universe will keep blowing up fast and forever.

Of course, the observers have caveats about their observations. The distances estimated for the clusters are one possible source of error. Inaccurate distances might mean the clusters are not clusters at all, only galaxies at different distances superimposed on the sky in a way that makes them look like clusters: "[We're] looking back in two dimensions," said Dressler. "Things are piled against the sky." Because of such errors, theories are malleable. With the same data, said Evrard, "I've written papers that work with a low omega and with a high omega. It doesn't take even a very clever theorist."

So the plans for the future are to make more observations. The sky is divided into 41,000 square degrees, and Gunn's optical survey covered only six of them. Those six, says Postman, took 3 years; with newer detectors, "you could map this in 4 nights." Another optical survey team—Postman, Hoessel, William Oegerle from STScI, and Tod Lauer from the National Optical Astronomy Observatories—is now using the telescope at Kitt Peak National Observatory with new detectors to map distant clusters to a red shift of 1.0. They are focusing on a region covering 16 square degrees, about the size of, and roughly in the same place as, the bowl of the Big Dipper. The Deep Extragalactic Evolutionary Probe, or DEEP, will use an instrument built by the University of California and others for the Keck telescope to map 12 1-degree patches to red shifts of 0.6. Still another survey, the Sloan Digital Sky Survey (a collaboration between Princeton University, the Institute for Advanced Study, Fermilab, the University of Chicago, Japan National University, and Johns Hopkins University), will take a much broader view of the sky, mapping nearly 4000 degrees to a red shift of 0.2. And x-ray astronomers in Italy and the United States have proposed a new satellite telescope, the Wide Field X-Ray Telescope, to map clusters over 100 square degrees, to a red shift of 2.0. Richard Burg of Johns Hopkins University, principal investigator on the x-ray telescope, says the proposal is in NASA's hands and—if all goes well—launch is 5 years off. If their plans work out, these researchers may be able to tell us how the universe will end.

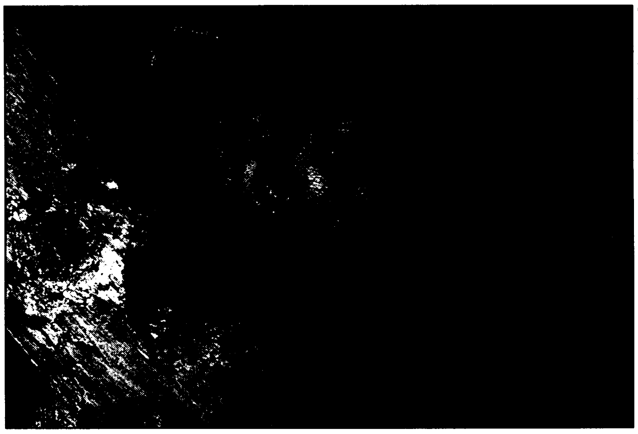
–Ann Finkbeiner

Ann Finkbeiner is a science writer based in Baltimore, Maryland.

PRIMATE BEHAVIOR

Nocturnal Researchers Tune Their Ears to Our Ancestors

DURHAM, NORTH CAROLINA—Primate behavior has become a favorite topic in the past few years, as researchers explore how biology influences behavior, and the public laps up books and movies on primatologists like Jane Goodall and Dian Fossey. Not surprisingly, gorillas and chimpanzees—humans' closest kin—have been the stars of the show. Like us, these big apes are active while the sun is up, so researchers seeking to understand their behavior can adopt a simple, if time-consuming strategy: They watch.



ANDREW YOUNG/ARCHIPELAGO FILMS

The ears have it. The endangered aye-aye relies on hearing to find food and scent to communicate.

But there's also a whole group of primitive primates who feed and mate in the dark, including exotic creatures such as galagos, lorises, lemurs, and tarsiers. Because of their secretive and hard-to-study lifestyle, these "nocturnal prosimians" have been left in shadow compared to their sun-loving cousins. Nevertheless, an intrepid band of researchers, who gathered recently at Duke University,* insists that these primitive primates are well worth the extra effort it takes to study them. Since the first primates were probably nocturnal, today's prosimians are a unique scientific resource, a window into the evolution of primates at least 50 million years ago, says Ken Glander of Duke. And since many of these species are dwindling in number, behavioral research has taken on a new urgency.

At the Duke meeting, scientists demonstrated that although they labor in the dark, they've found the key to understanding their subjects. The trick, says Simon Bearder of Oxford Brookes University in Oxford, England, is to think like a nocturnal primate: Focus on sound and scent, instead of sight. "We're finally beginning to get inside the minds of these creatures—who after all are descended from our own ancestors—to see what it's like to be a creature of scent and hearing. Just because they don't see each other much doesn't mean they don't know whose home range overlaps with whose," says Alison Jolly of Princeton University.

By analyzing calls and scent marking behavior, scientists are finding unexpected diversity among the nocturnal prosimians, in terms of both numbers of species and behavior. Once thought to have relatively simple social structures, these prosimians are now known to have a complex repertoire of behaviors and communications, as do their cousins on the day shift.

Take the aye-aye, *Daubentonia madagascariensis*. One of the many prosimians found only on the island of Madagascar, the aye-aye is considered the world's most endangered primate because it's the only member of its family left. And the aye-aye is definitely a solitary creature. Adults spend more than 80% of their time alone and rarely if ever sleep together, says Eleanor Sterling, who presented the first long-term study of aye-ayes in the wild, done for her Ph.D. thesis at Yale University.

Despite this lust for solitude, there is a distinct social dimension to the aye-aye world. Different individuals occupy the same nest on subsequent nights, and they are well aware of the foraging areas of others. Females, for example, apparently stake out distinct home ranges and were never observed straying into another female's range. The invisible boundaries are apparently drawn by scent marks, left by streaking urine along a branch. "They communicate on a level that we do not," says Sterling, who spent 2 years trailing aye-ayes through the dark, aided by radio collars, dim flashlights, and two Malagasy guides. "If you're leaving scent marks all over, you're telling the others a lot, although we can't necessarily read those marks."

Smell isn't the only sense that helps nocturnal creatures navigate in the dark: They're keen listeners as well, and their calls

*"Creatures of the Dark: The Nocturnal Prosimians," 9-12 June 1993.