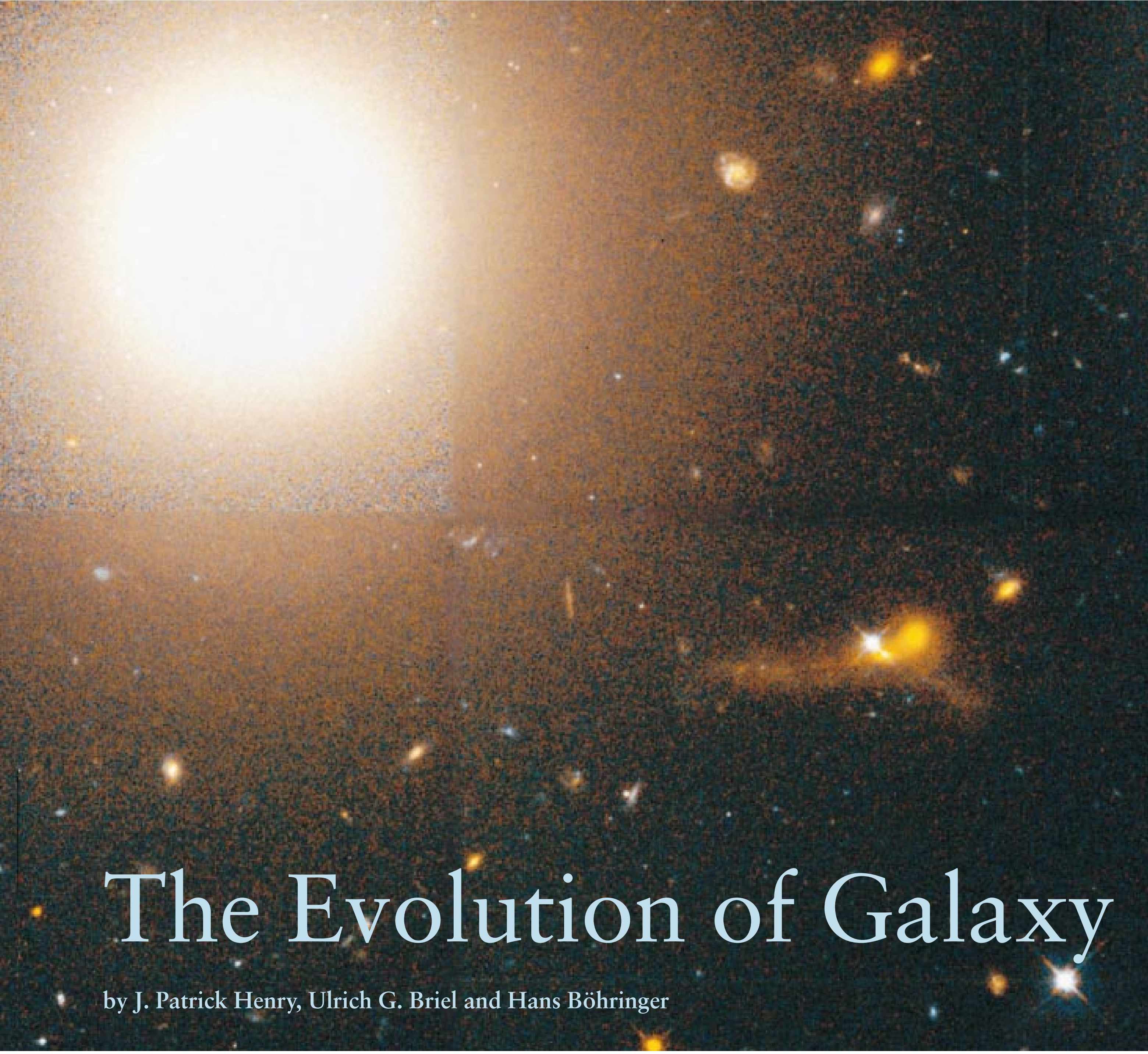


The Evolution of Galaxy

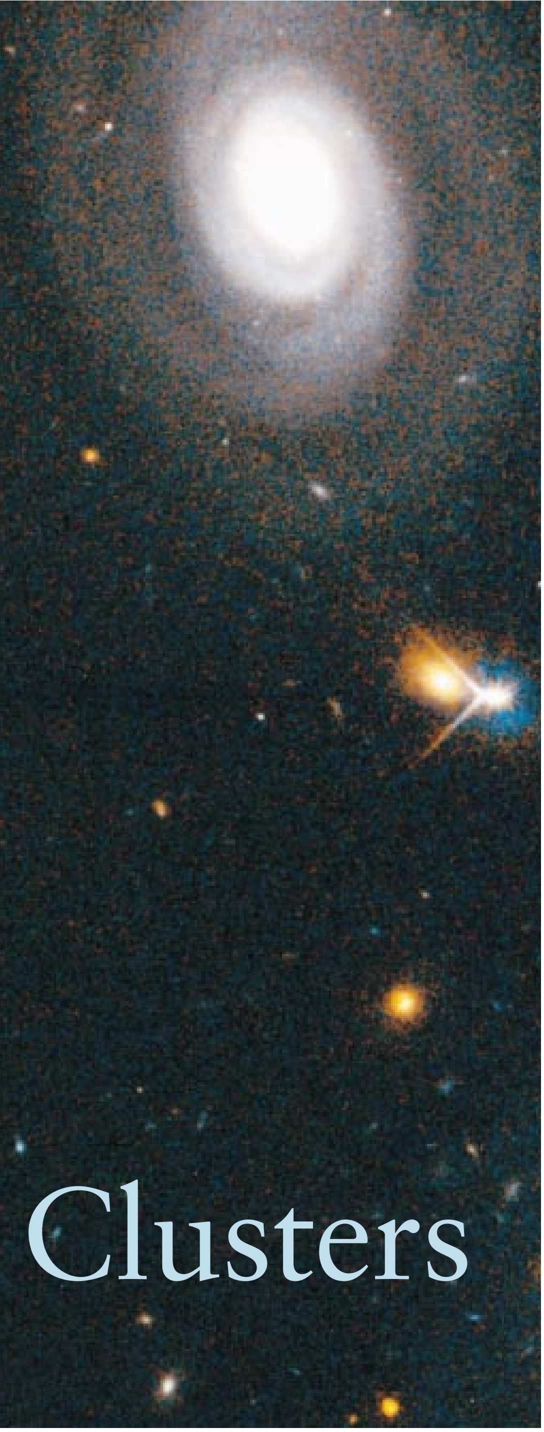
by J. Patrick Henry, Ulrich G. Briel and Hans Böhringer

The royal Ferret of Comets was busy tracking his prey. On the night of April 15, 1779, Charles Messier watched from his Paris observatory as the Comet of 1779 slowly passed between the Virgo and Coma Berenices constellations on its long journey through the solar system. Messier's renown in comet spotting had inspired the furry moniker from King Louis XV, but on this night he took his place in astronomy history books for a different reason. He noticed three fuzzy patches that looked like comets yet did not move from night to night; he added them to his list of such impostors so as not to be misled by them during his real work, the search for comets. Later he commented that a small region on the Virgo-Coma border contained 13 of the 109 stationary splotches that he, with the aid of Pierre Mechain, eventually identified—the Messier objects well known to amateur and professional astronomers today.

As so often happens in astronomy, Messier found something completely different from what he was seeking. He had discovered the first example of the most massive things in the universe held together by their own gravity: clusters of galaxies. Clusters are assemblages of galaxies in roughly the same way that galaxies are assemblages of stars. On the cosmic organizational chart, they are the vice presidents—only one level below the universe itself. In fact, they are more massive relative to a human being than a human being is relative to a subatomic particle.

In many ways, clusters are the closest that astronomers can get to studying the universe from the outside. Because a cluster contains stars and galaxies of every age and type, it represents an average sample of cosmic material—including the dark matter that choreographs the movements of celestial objects yet

The most massive objects in the universe are huge clusters of galaxies and gas that have slowly congregated over billions of years. The process of agglomeration may now be ending



Clusters

WILLIAM A. BAUM *University of Washington*, HUBBLE SPACE TELESCOPE WFPC TEAM AND SPACE TELESCOPE SCIENCE INSTITUTE

TWO BRIGHT GALAXIES in the Coma cluster, one elliptical (*top left*) and the other spiral (*top right*), appear in this composite Hubble Space Telescope image taken in 1994. The Coma cluster, located some 300 million light-years away, was one of the first galaxy clusters identified by astronomers. Most of the other splotches in the image are galaxies at even greater distances.

cannot be seen by human eyes. And because a cluster is the result of gravity acting on immense scales, its structure and evolution are tied to the structure and evolution of the universe itself. Thus, the study of clusters offers clues to three of the most fundamental issues in cosmology: the composition, organization and ultimate fate of the universe.

A few years after Messier's observations in Paris, William Herschel and his sister, Caroline, began to examine the Messier objects from their garden in England. Intrigued, they decided to search for others. Using substantially better telescopes than their French predecessor had, they found more than 2,000 fuzzy spots—including 300 in the Virgo cluster alone. Both William and his son, John, noticed the lumpy arrangement of these objects on the sky. What organized these objects (which we now know to be galaxies) into the patterns they saw?

A second question emerged in the mid-1930s, when astronomers Fritz Zwicky and Sinclair Smith measured the speeds of galaxies in the Virgo cluster and in a slightly more distant cluster in Coma. Just as the planets orbit about the center of mass of the solar system, galaxies orbit about the center of mass of their cluster. But the galaxies were orbiting so fast that their collective mass could not provide enough gravity to hold them all together. The clusters had to be nearly 100 times as heavy as the visible galaxies, or else the galaxies would have torn out of the clusters long ago. The inescapable conclusion was that the clusters were mostly made of unseen, or "dark," matter. But what was this matter?

These two mysteries—the uneven distribution of galaxies in space and the unknown nature of dark matter—continue to confound astronomers. The former became especially puzzling after the discovery in the mid-1960s of the cosmic microwave background radiation. The radiation, a snapshot of the universe after the big bang and before the formation of stars and galaxies, is almost perfectly smooth. Its tiny imperfections somehow grew to the structures that exist today, but the process is still not clear [see "Very Large Structures in the Universe," by Jack O. Burns; SCIENTIFIC AMERICAN, July 1986]. As for dark matter, astronomers have learned a bit more about it since the days of Zwicky. But they are still in the uncomfortable position of not knowing what most of the universe is made of [see "Dark Matter in the Universe," by Lawrence M. Krauss; SCIENTIFIC AMERICAN, December 1986].

Light from Dark Matter

Impelled by these mysteries, the pace of discovery in the study of clusters has accelerated over the past 40 years. Astronomers now know of some 10,000 of them. American astronomer George Abell compiled the first large list in the early 1950s, based on photographs of the entire northern sky taken at Palomar Observatory in California. By the 1970s astronomers felt they at least understood the basic properties of clusters: They consisted of speeding galaxies bound together by huge amounts of dark matter. They were stable and immutable objects.

Then came 1970. In that year a new satellite, named Uhuru ("freedom" in Swahili) in honor of its launch from Kenya, began observing a form of radiation hitherto nearly inaccessible to astronomers: x-rays. Edwin M. Kellogg, Herbert Gursky and their colleagues at American Science and Engineering, a small company in Massachusetts, pointed Uhuru at the Virgo and Coma clusters. They found that the clusters consist not only of galaxies but also of huge amounts of gas threading the space between the galaxies. The gas is too tenuous to be seen in visible light, but it is so hot—more than 25 million degrees Celsius—that it pours out x-rays.

In short, astronomers had found some of the dark matter—20 percent of it by mass. Although the gas is not enough to solve the dark matter mystery completely, it does account for more mass than all the galaxies put together. In a way, the term "clusters of galaxies" is inaccurate. These objects are balls of gas in which galaxies are embedded like seeds in a watermelon

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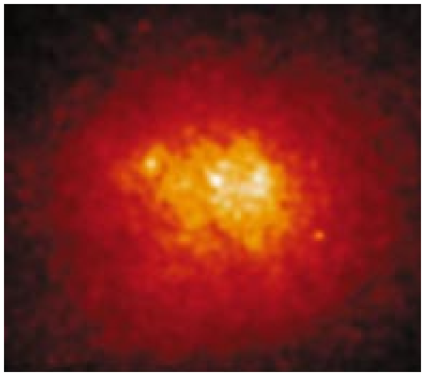


COMA CLUSTER looks different in visible light (*left*) and in x-rays (*right*). In visible light, it appears to be just an assemblage of galaxies. But in x-rays, it is a gargantuan ball of hot gas some five million light-years across.

[see "Rich Clusters of Galaxies," by Paul Gorenstein and Wallace Tucker; Scientific American, November 1978].

Since the early 1970s, the x-ray emission has been scrutinized by other satellites, such as the Einstein X-Ray Observatory, the Roentgen Satellite (ROSAT) and the Advanced Satellite for Cosmology and Astrophysics (ASCA). Our own research mainly uses ROSAT. The first x-ray telescope to record images of the entire sky, ROSAT is well suited for observations of large diffuse objects such as clusters and is now engaged in making detailed images of these regions. With this new technology, astronomers have extended the discoveries of Messier, Zwicky and the other pioneers.

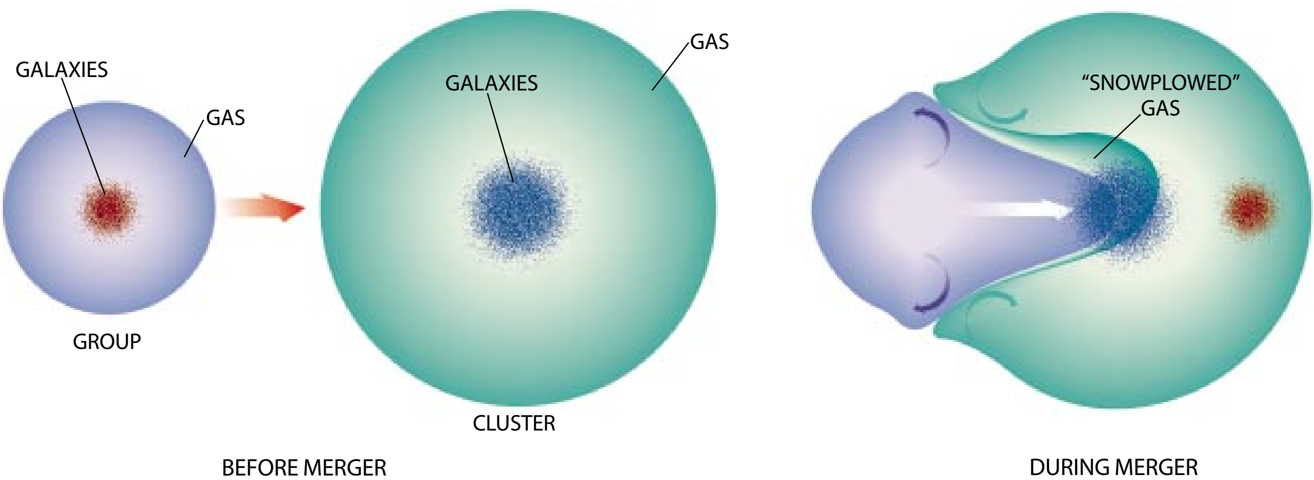
When viewed in x-rays, the Coma cluster has a mostly regular shape with a few lumps [*see left illustration on page 56*]. These lumps appear to be groups of galaxies—that is, miniature clusters. One lump to the southwest is moving into the main body of the cluster, where other lumps already reside. Virgo, by comparison, has an amorphous shape. Although it has regions of extra x-ray emission, these bright spots are coming from some of the Messier galaxies rather than from clumps of gas [*see right illustration on page 56*]. Only the core region in the northern part of Virgo has a nearly symmetrical structure.

Such x-ray images have led astronomers to conclude that clusters form from the merger of groups. The lumps in the main body of the Coma cluster presumably represent groups that have already been drawn in but have not yet been fully assimilated. Virgo seems to be in an even earlier stage of formation. It is still pulling in surrounding material and, at the current rate of progress, will look like Coma after a few billion years. This dynamic view of clusters gobbling up and digesting nearby matter is in stark contrast to the static view that astronomers held just a few years ago.

Taking Their Temperature

Ever since astronomers obtained the first good x-ray images in the early 1980s, they have wanted to measure the variation of gas temperature across clusters. But making these measurements is substantially more difficult than making images, because it requires an analysis of the x-ray spectrum for each point in the cluster. Only in 1994 did the first temperature maps appear.

The maps have proved that the formation of clusters is a violent process. Images of the cluster Abell 2256, for example, show that x-ray emission has not one but rather two peaks. The western peak is slightly flattened, suggesting that a group slamming into the main cluster has swept up material just as a snowplow does. A temperature map supports this interpretation [*see illustration on opposite page*]. The western peak, it turns out, is comparatively cool; its temperature is characteristic of the gas in a group of galaxies. Because groups are smaller than clusters, the gravitational forces within them are weaker; therefore, the speed of the gas molecules within them—that is, their temperature—is lower. A typical group is 50 trillion times as massive as the sun and has a temperature of 10 million degrees C. By comparison, a typical cluster weighs 1,000 trillion suns and registers a temperature of 75 million degrees C; the heaviest known cluster is five



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ABSORPTION OF GALAXY GROUP allows a cluster to grow to colossal size. Pulled in by gravity, the group slams into the cluster, pushing gas out the sides. The galaxies themselves pass through the cluster, their progress unimpeded by the tenuous gas. Eventually the galaxies and gas mix together, forming a unified cluster that continues to draw in other groups until no more are to be found.

times as massive and nearly three times as hot.

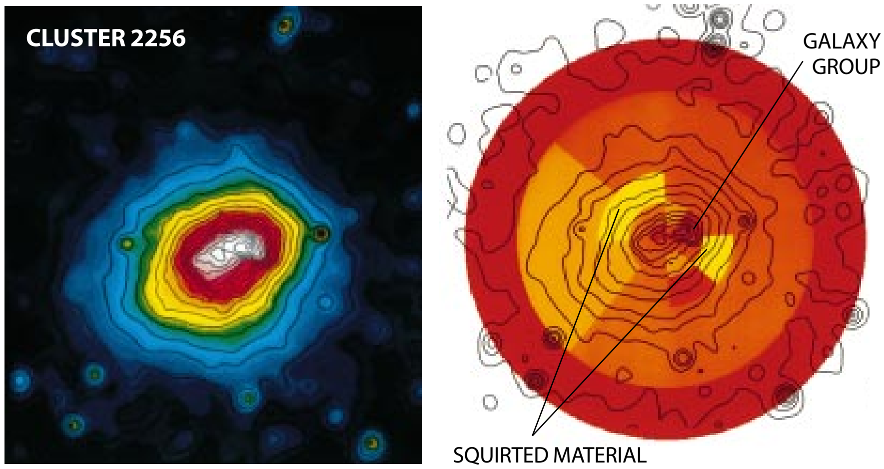
Two hot regions in Abell 2256 appear along a line perpendicular to the presumed motion of the group. The heat seems to be generated as snowplowed material squirts out the sides and smashes into the gas of the main cluster. In fact, these observations match computer simulations of merging groups. The group should penetrate to the center of the cluster in several hundred million years. Thus, Abell 2256 is still in the early stages of the merger.

The late stages of a merger are apparent in another cluster, Abell 754. This cluster has two distinguishing features. First, optical photographs show that its galaxies reside in two clumps. Second, x-ray observations reveal a bar-shaped feature from which the hot cluster gas fans out. One of the galaxy clumps is in the bar region, and the other is at the edge of the high-temperature region to the west.

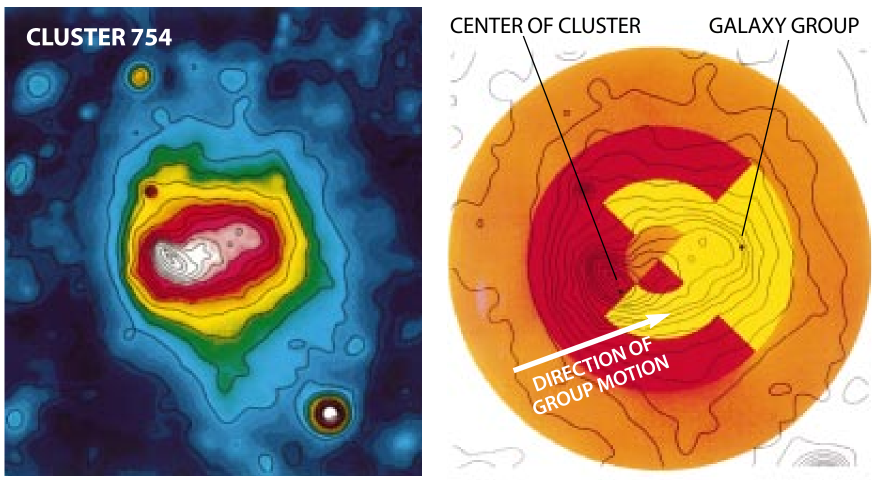
Theorists can explain this structure with an analogy. Imagine throwing a water balloon, which also contains some pebbles, into a swimming pool. The balloon represents the merging group: the water is gas, and the pebbles are galaxies. The swimming pool is the main cluster. When the balloon hits the water in the pool, it ruptures. Its own water stays at the surface and mixes very slowly, but the pebbles can travel to the other side of the pool. A similar process apparently took place in Abell 754. The gas from the merging group was suddenly stopped by the gas of the cluster, while the group galaxies passed right through the cluster to its far edge.

A third cluster, Abell 1795, shows what a cluster looks like billions of years after a merger. The outline of this cluster is perfectly smooth, and its temperature is nearly uniform, indicating that the cluster has assimilated all its groups and settled into equilibrium. The exception is the cool region at the very center. The lower temperatures occur because gas at the center is dense, and dense gas emits x-rays more efficiently than tenuous gas. If left undisturbed for two or three billion years, dense gas can radiate away much of its original energy, thereby cooling down.

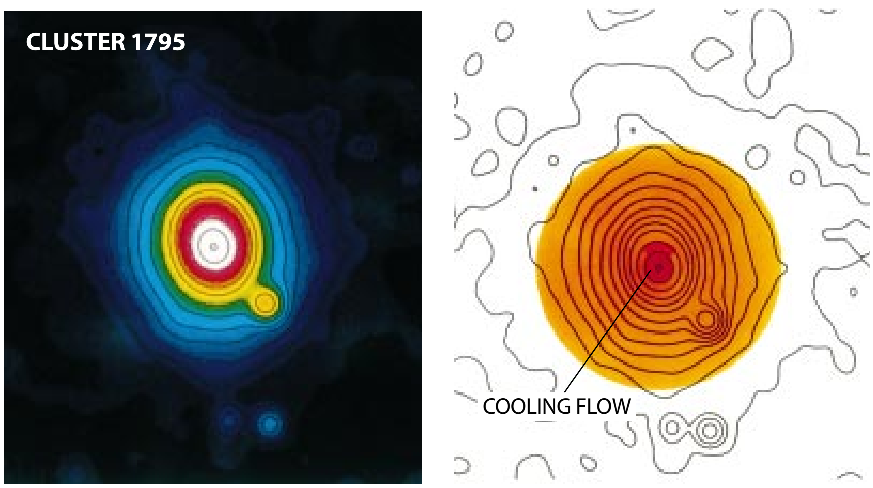
As the gas cools, substantial amounts of lukewarm material build up—enough for a whole new galaxy. So where has all this material gone? Despite exhaustive searches, astronomers have yet to locate conclusively any pockets of tepid gas. That the cluster gas is now losing



THREE GALAXY CLUSTERS are at different stages in their evolution, as shown in these x-ray images (*left column*) and temperature maps (*right column*). The first cluster, Abell 2256, is busily swallowing a small group of galaxies, which is identified by its relatively low temperature. On the map red is comparatively cool, orange intermediate and yellow hot.



The second cluster, Abell 754, is several hundred million years further along in its digestion of a galaxy group. The hapless group probably entered from the southeast, because the cluster is elongated in that direction. The galaxies of the group have separated from their gas and passed through the cluster.



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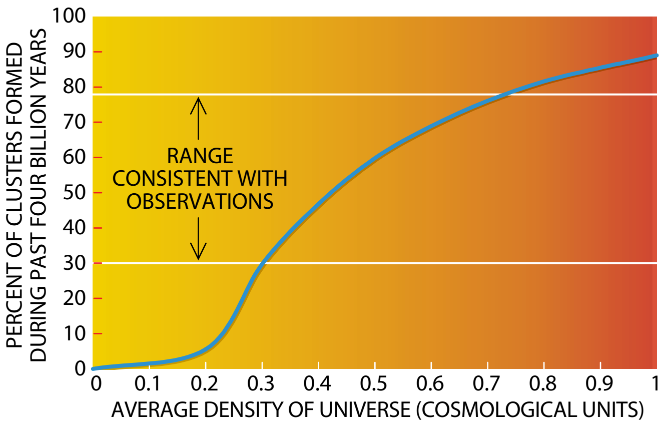
The third cluster, Abell 1795, has gone several billion years since its last meal. Both its x-ray brightness and gas temperature are symmetrical. At the core of the cluster is a cool spot, a region of dense gas that has radiated away much of its heat.

From Cluster Evolution to Cosmic Evolution

Ever since the big bang, the universe has been expanding. All objects not bound to one another by gravity or some other force are being pulled apart. But will the cosmic expansion continue forever, or will the gravity of all the matter in the universe be sufficient to halt it? Traditional attempts to answer the question have foundered because they require a careful census of the total amount of matter in the universe—and that is difficult, because most of it is invisible dark matter.

Now there is a new approach made possible by studying the evolution of galaxy clusters. Over time, clusters grow as they accrete matter, until the matter within their gravitational reach is exhausted. The more matter there is, the faster and bigger they can grow (*right*). If the universe has enough matter to come to a halt, then fewer than 10 percent of the massive clusters that exist today were in place four billion years ago—and new clusters should still be forming and growing today. But if the universe has only one quarter of the matter needed to stop its expansion, then all the massive clusters were in place four billion years ago—and no further growth has taken place since then.



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The observed cluster evolution rate favors the latter scenario: because galaxy clusters have essentially stopped growing, there must be comparatively little matter in the universe. Therefore, the cosmos will expand forever (unless there exists material with exotic physical properties, such as a gravitational repulsion that varies with time). Other recent measurements of cosmic expansion, using distant supernovae and other markers, agree. Although the case is not closed, several independent pieces of evidence now make it more likely that astronomers do know the ultimate fate of the cosmos. *—J.P.H.*

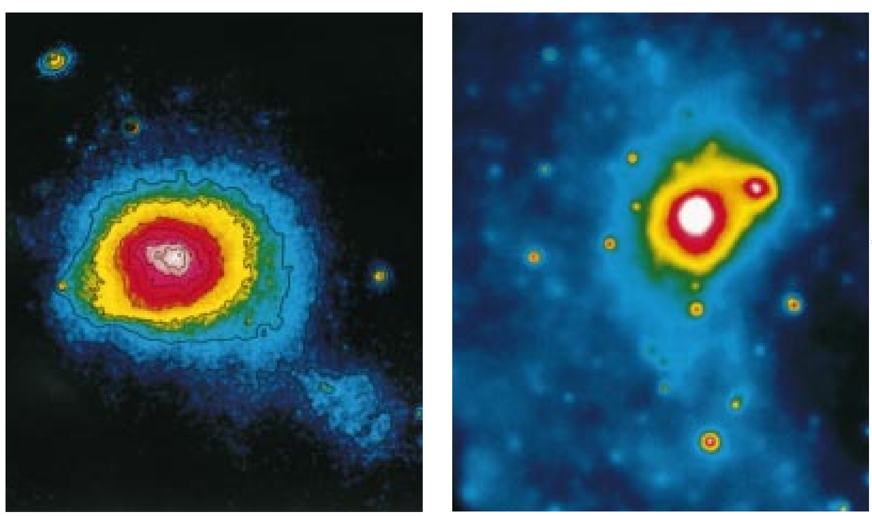
heat is obvious from the temperature maps. Perhaps the heat loss started only fairly recently, or perhaps the collision of galaxy groups prevents cool gas from collecting in one spot. These so-called cooling flows remain yet another unsolved mystery.

Bottoms Up

The sequence represented by these three Abell clusters is probably undergone by every cluster as it grows. Galaxy groups occasionally join the cluster; with each, the cluster gains hot gas, bright galaxies and dark matter. The extra mass creates stronger gravitational forces, which heat the gas and accelerate the galaxies. Most astronomers believe that almost all cosmic structures agglomerated in this bottom-up way. Star clusters merged to form galaxies, which in turn merged to form groups of galaxies, which are now merging to form clusters of galaxies. In the future it will be the clusters' turn to merge to form still larger structures. There is, however, a limit set by the expansion of the universe. Eventually, clusters will be too far apart to merge. Indeed, the cosmos may be approaching this point already.

By cosmological standards, all the above-mentioned clusters (Coma, Virgo, and Abell 2256, 754 and 1795) are nearby objects. Astronomers' efforts to understand their growth are analogous to understanding human growth from a single photograph of a crowd of people. With a little care, you could sort the people in the picture into the proper age sequence. You could then deduce that as people age, they generally get taller, among other visible changes.

You could also study human growth by examining a set of photographs, each containing only people of a certain age—for example, class pictures from grade school, high school and college. Similarly, astronomers can observe clusters at ever increasing distances, which correspond to ever earlier times. On average, the clusters in a more distant sample are younger than those in a nearby one. Therefore, researchers can piece together "class photos" of clusters of different ages. The advantage of this approach is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X-RAY IMAGES of Coma (*left*) and Virgo (*right*) clusters show the hot intergalactic gas that dominates the luminous part of these structures. The gas in Coma has a more regular shape than that in Virgo, suggesting that the cluster has reached a more advanced stage of formation. Both clusters are surrounded by infalling material.

that it lets astronomers work with a whole sample of clusters, rather than just a few individual clusters. The disadvantage is that the younger objects are too far away to study in detail; only their average properties can be discerned.

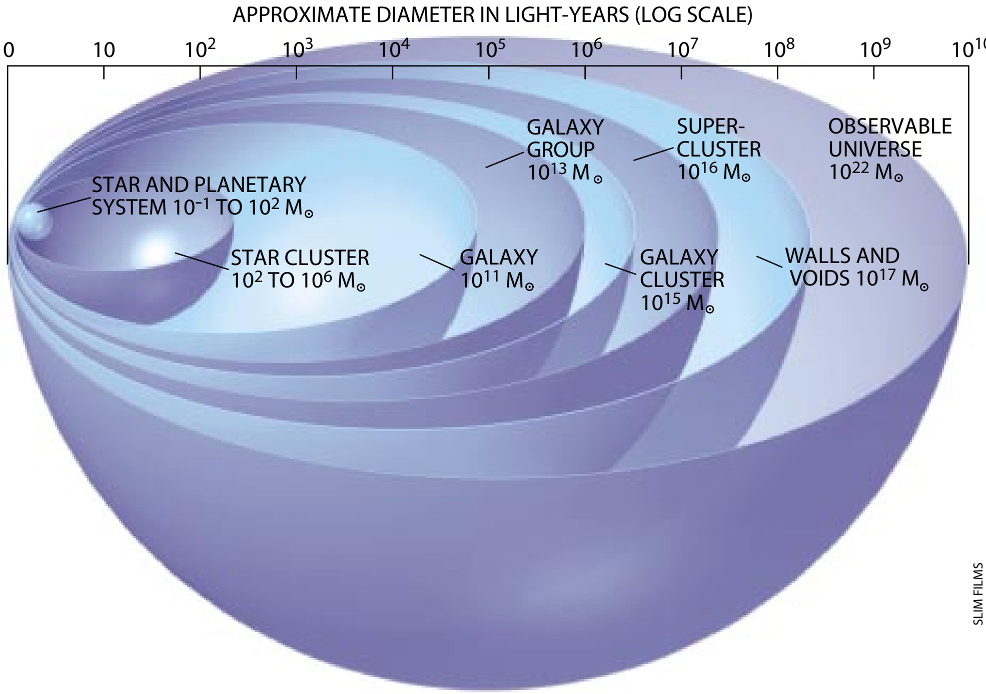
One of us (Henry) applied this method to observations from the ASCA x-ray satellite. He found that distant, younger clusters are cooler than nearby, older ones. Such a temperature change shows that clusters become hotter and hence more massive over time—further proof of the bottom-up model. From these observations researchers have estimated the average rate of cluster evolution in the universe. The rate, which is related to the overall evolution of the universe and to the nature of the dark matter, implies that the universe will expand forever [*see box on opposite page*].

New x-ray observations may shed light on the remaining dark matter in clusters. By the end of 2000 there will be three advanced x-ray observatories in orbit: the Advanced X-Ray Astrophysics Facility from the U.S., the X-ray Multi-mirror Mission from Europe and ASTRO-E from Japan.

In the meantime, observations of another form of radiation, known as extreme ultraviolet light, are yielding mysteries of their own. The extreme ultraviolet has an energy that is only slightly lower than that of x-rays. It is heavily absorbed by material in our galaxy, so astronomers assumed that most clusters are not visible in this wavelength band. But recently Richard Lieu of the University of Alabama at Huntsville, C. Stuart Bowyer of the University of California at Berkeley and their colleagues studied five clusters using the sensitive Extreme Ultraviolet Explorer satellite.

These clusters, they discovered, shine brightly in the extreme ultraviolet. In some ways, this discovery was as unexpected as the first detection of x-rays from clusters in the early 1970s. Although some of the radiation comes from the same gas that generates the x-rays, there appears to be an additional source in at least some of the clusters. This finding is very new and has not yet been explained. Perhaps astronomers are seeing another component of the clusters' dark matter for the first time. The upcoming x-ray facilities may identify this new component.

Those of us involved in this work feel a special bond with Charles Messier as he strained to glimpse those faint patches of light in Virgo, not knowing their true significance. As advanced as our technology has become, we still strain to understand these clusters. We feel a bond with future observers as well, for science advances in a continuous process of small increments. We have been helped by those who preceded us; we share our new understanding with those who follow. SA



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HIERARCHY OF COSMIC STRUCTURES ranges from stars and planets to the universe itself. The largest objects held together by gravity are galaxy clusters with masses up to 10^{15} times that of the sun (denoted as $M_\odot$). Although there is a higher level of organization consisting of superclusters and great walls, these patterns are not bound gravitationally. On even larger scales, the universe is featureless. Astronomers think most of these structures form from the progressive agglomeration of smaller units.

The Authors

J. PATRICK HENRY, ULRICH G. BRIEL and HANS BÖHRINGER are x-ray astronomers who study clusters of galaxies. The first two met in the late 1970s while working at the Smithsonian Astrophysical Observatory on one of the instruments on the Einstein X-ray Observatory satellite. Henry is now an astronomy professor at the University of Hawaii. He says he enjoys sitting on his lanai and thinking about large-scale structure while watching the sailboats off Diamond Head. Briel and Böhringer are staff members of the Max Planck Institute for Extraterrestrial Physics in Garching. Briel is an observer who tested and calibrated the ROSAT instrument that made the temperature maps discussed in this article. Böhringer is a theorist who studies galaxy clusters, cosmology and the interstellar medium.

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