The gravitational binding means that the galaxies and other material within a mature cluster have settled into an overall dynamic equilibrium. Galaxies buzz around within it and are kept from flying apart by dark matter, a mysterious form of matter that has eluded detection except through its gravitational effects. The interactions of these components produce a rich array of phenomena that astronomers are only beginning to grasp.

Like metropolises on Earth, clusters are more than the sum of their inhabitants. Processes occurring at the scale of a cluster can dictate events on much smaller scales, such as the growth of galaxies and the fueling of the supermassive black holes at the hubs of those galaxies. In turn, the black holes blow out huge amounts of high-speed material that can drive the evolution of the entire cluster. At first glance, these interconnections between large and small are enigmatic. The diameters of the black holes in question are smaller than the solar system. For them to affect an entire galaxy cluster would be like a blueberry affecting the entire Earth.

For a black hole to affect an entire galaxy cluster would be like a blueberry affecting the entire EARTH.

The Case of the Disappearing Gas

THESE INTERACTIONS explain some long-standing paradoxes in the urban life of the cosmos. One is the so-called cooling flow problem, which has to do with multimillion-degree gas that fills the space between the galaxies in a cluster. If the galaxies within a cluster are the urban cores of the megacity, this gas is the suburban sprawl. Like the suburbs that surround most American downtowns, the gas is actually the more populated region: it contains more mass than all the stars in all the galaxies in the cluster.

The gas, which is heated primarily by the slow gravitational collapse of the cluster, gives off x-rays. Optical telescopes cannot see the gas, and x-rays cannot penetrate Earth's atmosphere, so the discovery and study of this gas has depended on orbiting observatories. Two decades ago astronomers peering with NASA's Einstein X-ray Observatory and other instruments noticed that the x-rays carry away so much energy that the gas should steadily cool off and settle into the center of the cluster—thus the term "cooling flow." One of us (Fabian) led the way in investigating these flows using Einstein and later Germany's ROSAT x-ray satellite. He and his colleagues calculated the flows would have quite dramatic effects. If they persisted for a billion years, the gas deposited in the central regions of the cluster could form trillions of new stars.

The only trouble was, no one could find them. Observers looked in vain for large amounts of cool gas and hordes of newly formed stars. If a black hole had swallowed them all, it would weigh as much as a trillion stars, and not even the biggest black hole is that massive. Another one of us (Tucker) maintained that large-scale, long-term cooling flows do not exist. A possible explanation was that long-lasting outbursts of energy from the central galaxy of the cluster heated the gas enough to offset the radiative cooling. Radio astronomers had for years been accumulating evidence for such activity. But it was questionable whether the outbursts provided enough energy distributed over a large enough volume to halt the cooling flows, so the paradox remained: the hot cluster gas must cool, but the end product of the cooling mysteriously escaped detection.

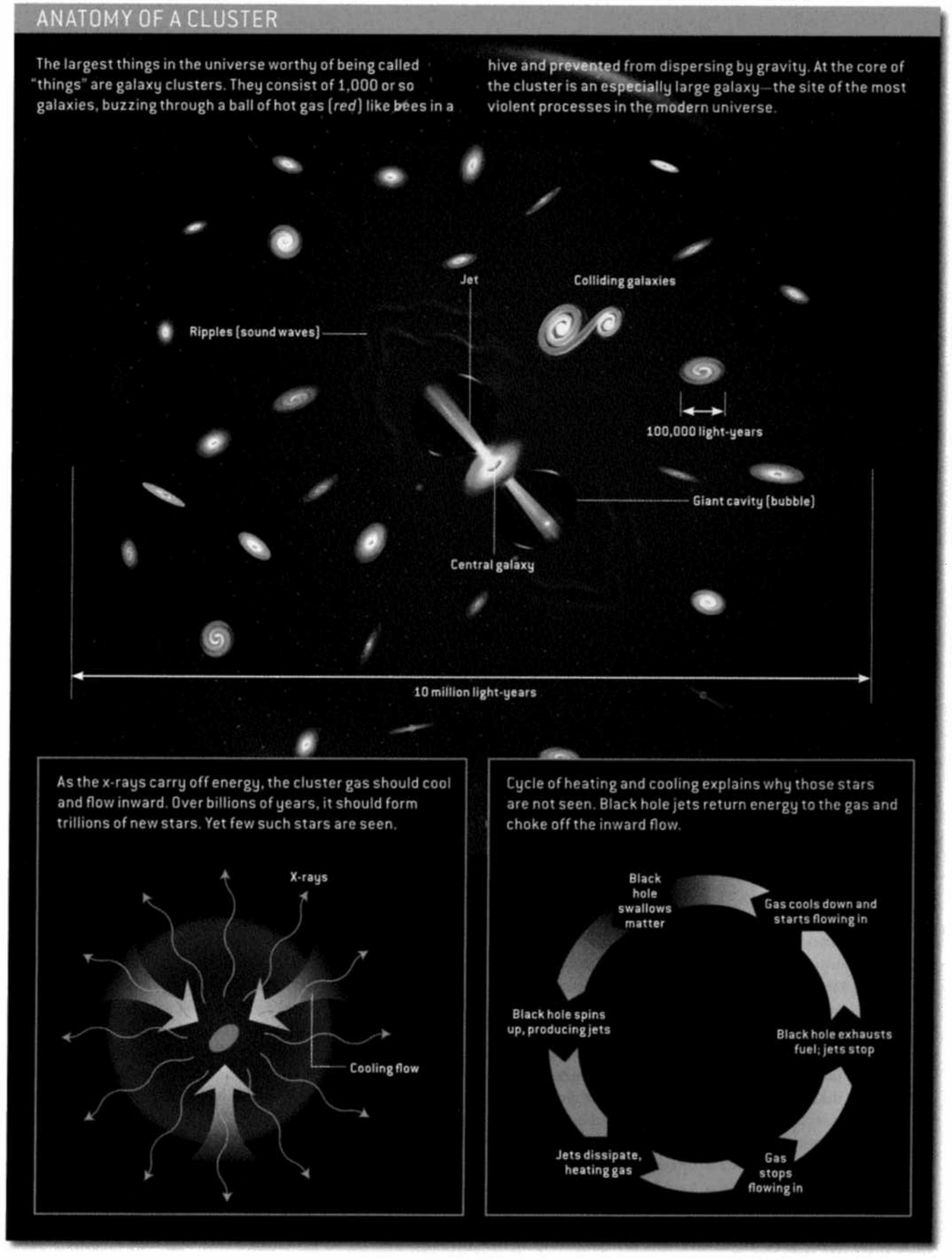
Resolving this paradox was a major goal of two powerful x-ray telescopes launched in 1999: NASA's Chandra X-ray Observatory and the European Space Agency's XMM-Newton. Because the gas in clusters radiates away its energy fairly slowly, it preserves a record of activity in the clusters over the past few billion years. For instance, it retains the elements and energy injected into it by supernova explosions in the cluster galaxies. Like archaeologists unearthing the past, astronomers have used the new telescopes to excavate the relics present in galaxy clusters and piece together their history.

Bubble, Bubble

THE BRIGHTEST CLUSTER observed by x-ray instruments is the Perseus cluster because of its high intrinsic luminosity and relative cosmic proximity to Earth (about 300 million light-years). In the 1990s ROSAT discovered two vast holes in the x-ray gas in the central 50,000 light-years of the cluster. They look like an hourglass centered on the giant galaxy

Overview/*Monster Bubbles*

- Using a combination of radio and x-ray telescopes, astronomers have discovered vast bubbles of high-energy particles hundreds of thousands of light-years across. The energy required to create these structures beggars belief—it is as if 100 million stars went supernova at once.
- The only thing capable of creating such a monster is a giant black hole. Not all matter that comes close to a black hole is doomed. As magnetized hot gas swirls in an accretion disk toward a hole, strong electromagnetic forces build up and spit out some of the gas in a narrow jet.
- Not only can the jet create bubbles, it adds heat and magnetism to the intergalactic gas in a galaxy cluster, explaining long-standing puzzles in astronomy. The process appears to be a part of a multimillion-year cycle that regulates the growth of supergiant galaxies in the centers of clusters.



DON DIXON (*preceding pages*)

ALFRED T. KAMAJIAN (*top*); JANA BRENNING (*bottom*)