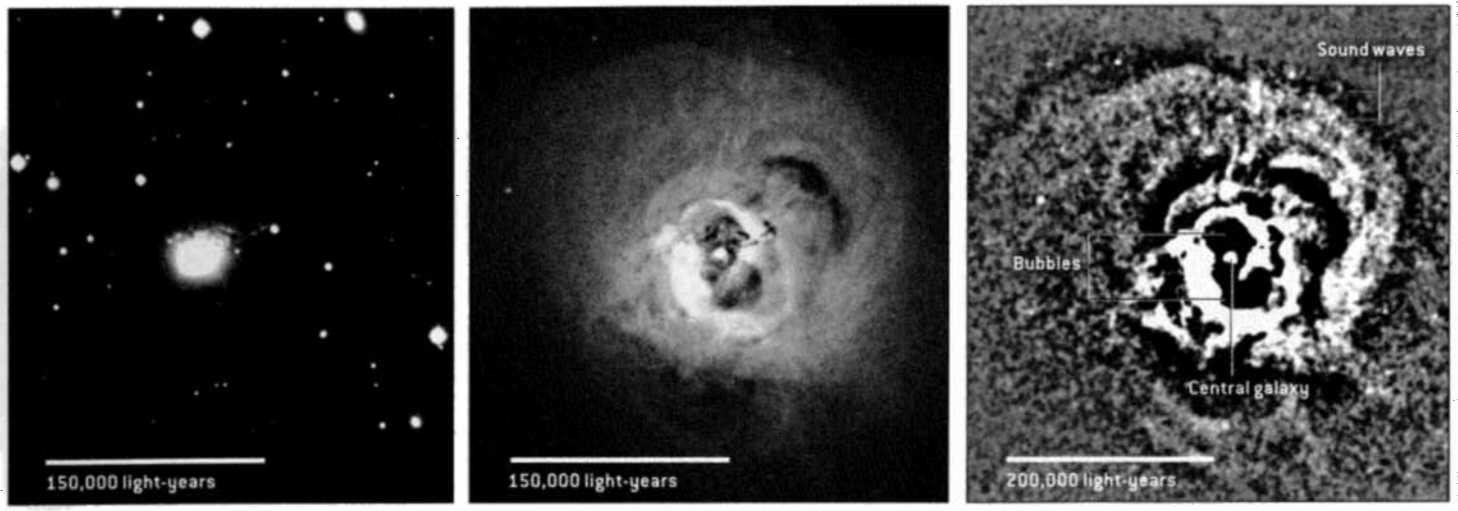

PERSEUS CLUSTER looks sedate when viewed in visible light (*left*) but comes alive when viewed in x-rays (*center*). The space between the galaxies is filled with hot gas threaded by bright loops, filaments and streaks. Two bubbles, which appear vacant in these images but actually contain high-energy particles, straddle the central galaxy, NGC 1275. Increasing the image contrast (*right*) brings out ripples, thought to be sound waves that transport energy to the intergalactic gas. For animations, visit chandra.harvard.edu/photo/2003/perseus/animations.html

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bridge at the time but has since left academia. The rotating black hole twists up the fabric of space around it, forcing the magnetic field in the infalling gas into a funnellike shape—an electromagnetic tornado that flings fields and charged particles outward in two opposing jets. Slowly spinning black holes produce feeble jets; most of the inflowing gas continues down into the hole and is lost forever. Rapidly spinning black holes, though, expel roughly a quarter of the inflowing gas.

Supermassive black holes in the centers of galaxies are expected to spin up over time as they accrete gas. By the time the black hole has swallowed enough gas to double its mass, its horizon, or outer boundary, should be whipping around at nearly the speed of light. According to Einstein's theory of relativity, the hole can never reach the speed of light no matter how much gas it devours; each additional clump of gas produces diminishing returns. A variety of observational methods for estimating the spin of black holes confirm that many are whirling rapidly enough to produce powerful jets. A similar phenomenon happens on a smaller scale. Stellar-mass black holes, with masses of a dozen suns (rather than a billion), can pump out powerful jets of particles at near the speed of light, heating and pushing aside ambient gas.

Calculations show that black hole jets have two major components: a matter-dominated outflow that moves at about a third of the speed of light, forming the outer sheath of the funnel, and an inner region along the axis of the funnel that contains a rarefied gas of extremely high energy particles. It is the inner region that carries much of the energy and creates the dramatic structures observed by radio and x-ray astronomers.

One of the most astounding features of jets is the pencil-thin shape that they can maintain despite traveling hundreds of thousands of light-years, far beyond the confines of their parent galaxies. Moreover, they manage to do this while radiating hardly any of their energy. The pressure of the gas near a black hole can get a jet started as a narrow beam, and it may be that inertia keeps the jet narrow, much the way a blast of water emerges from a hose or steam erupts from a high-pressure tea kettle. The tightly coiled magnetic field that is spun out with the jet may also play a role.

Regardless of the confining mechanism, the pressure of the gas through which jets move gradually takes its toll. The jets slow down and billow out, creating enormous magnetized clouds of high-energy particles. These clouds continue to expand, pushing out the surrounding gas to create the dark x-ray cavities observed by Chandra.

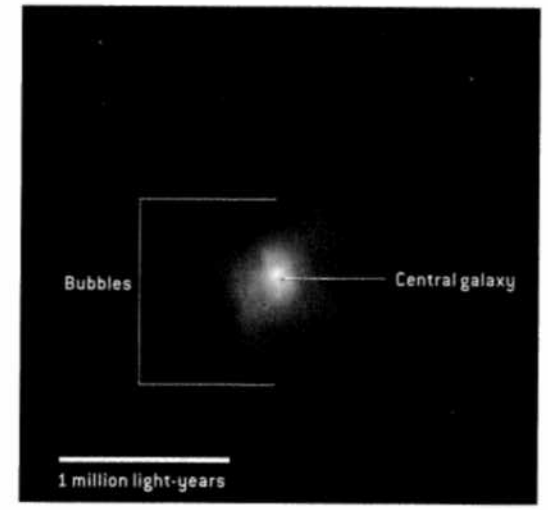
The Cosmic Hydrologic Cycle

THIS SEQUENCE OF EVENTS—gas falls into a rapidly spinning black hole to form outward-moving megajets that carve out gigantic bubbles of high-energy particles and heat vast volumes of space—is a blowback of truly cosmic proportions. The black hole is both responding to and influencing events on the scale of the entire galaxy cluster.

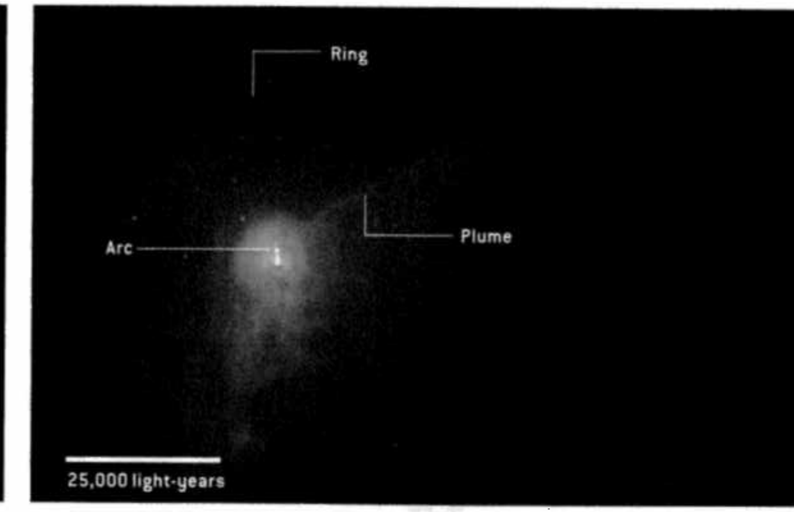
A likely scenario goes as follows. Initially the gas in the cluster is very hot, and the supermassive black hole in a centrally located large galaxy is quiet. Over about 100 million years, gas in the central region of the cluster cools and drifts toward the central galaxy in a cooling flow. Some of the gas in this cooling flow condenses into stars that become part of the central galaxy, and some sinks all the way down to feed the supermassive black hole. In so doing, it creates an accretion disk and activates high-power jets.

The jets blast through the galaxy and out into the cluster gas, where their energy converts to heat. The heat greatly diminishes the cooling flow, if not shutting it off altogether. It is a case of biting the hand that feeds: by shutting down the cooling flow, the supermassive black hole chokes off its own supply of gas and gradually goes dormant. The jets fade away, leaving the cluster gas without a heat source. Millions of years later the hot gas in the central region of the cluster finally cools sufficiently to initiate a new season of growth for the galaxy and its supermassive black hole, and thus the cycle continues.

This scenario is supported by high-resolution x-ray and radio images of the Virgo, Perseus, Hydra and other clusters, which show evidence of repetitive outbursts from the vicinity of the central galaxies' supermassive black holes. Magnetized rings, bubbles, plumes and jets ranging in size from a few thousand to a few hundred thousand light-years strongly suggest that intermittent violent activity has been going on in these clusters for hundreds of millions of years.



MOST POWERFUL ERUPTION EVER SEEN has been underway for 100 million years in the cluster MS 0735. The bubbles (*blue*) seen in this composite radio and x-ray image are 250 times more powerful than those in the Perseus cluster.



JETS POKING OUT OF GALAXY M87 in the Virgo cluster are relative weaklings—just 0.01 percent of the power of those in MS 0735—but make up for it with their fine details, including curved plumes (which are possibly the remnants of previous outbursts), arcs (possibly shock waves) and faint rings (possibly sound waves).

NASA/CXC/OHIO UNIVERSITY/B. McNAMARA ET AL. (*left*); NASA/CXC/W. FORMAN ET AL. (*right*)

One startling implication is that supermassive black holes are still growing at a rapid rate even in the present day. Astronomers had thought their growth had tapered off. In the case of cluster MS 0735, the activity indicates that the supermassive black hole has gulped down the equivalent of 300 million suns in the past 100 million years—nearly doubling in size and mass over that relatively brief interval. Yet the central black hole shows no other signs of activity, such as bright x-rays or visible light, which are usually emitted by active holes. It is only through the x-ray cavities that we can discern the properties of this extraordinary system.

Cosmic Consequences

THE SCENARIO IS ENRICHED by galaxy collisions, an ever present hazard in the central regions of galaxy clusters. A smaller galaxy passing too close to the giant central galaxy is torn asunder—its stars assimilated, some of its gas lost down the black hole drain, its own central black hole merged with the one in the giant galaxy. The enormous cavities observed in MS 0735 were probably the end result of a sequence of events initiated when a merging galaxy caused a huge influx of gas into a supermassive black hole.

The role of collisions in clusters may help scientists understand the evolution of galaxies in the early universe. In a sense, clusters are living fossils, the only places in the universe that retain the conditions that prevailed billions of years ago, when galaxies were closer together and mergers were common. A growing body of research indicates that many aspects of galaxy formation and evolution—the size and shape of galaxies, the rate of star formation—can be understood in terms of a cosmic cycle involving mergers of galaxies. Large-scale computer simulations by Philip F. Hopkins of the Harvard-Smithsonian Center for Astrophysics and his colleagues show that the mergers of gas-rich galaxies trigger bursts of star formation and inflow of gas into the central region. The inflowing gas fuels rapid growth of the supermassive black hole and intense radiation from its vicinity. Blowback ejects much of the gas from the galaxy, star formation abruptly slows, and accretion onto the black hole declines—until another merger occurs.

Most of the black hole feedback that shaped the evolution of galaxies occurred about eight billion to 10 billion years ago. Since then, the universe has thinned out too much—except in clusters. The blowback processes in clusters are similar (though not identical) to those that occurred in the ancient universe, allowing astronomers to study the jets, bubbles and waves that shaped our galaxy and others.

It may seem strange that supermassive black holes, objects with masses that range from a few million to hundreds of millions of solar masses, can have such an impact on galaxies whose masses range from a few billion to a few hundred billion solar masses, let alone galaxy clusters with masses measured in the hundreds of trillions of solar masses. The reason is the concentrated nature of supermassive black holes and their gravitational fields. Supermassive black holes are by far the largest supply of gravitational potential energy in an entire galaxy. By tapping this energy through accretion disks and the launching of megajets, blowback vastly increases the reach of these black holes—making it one of the most important processes at work in the universe. SA

MORE TO EXPLORE

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For the latest from the Chandra and XMM-Newton orbiting observatories, see **http://chandra.harvard.edu** and **http://xmm.esac.esa.int/**