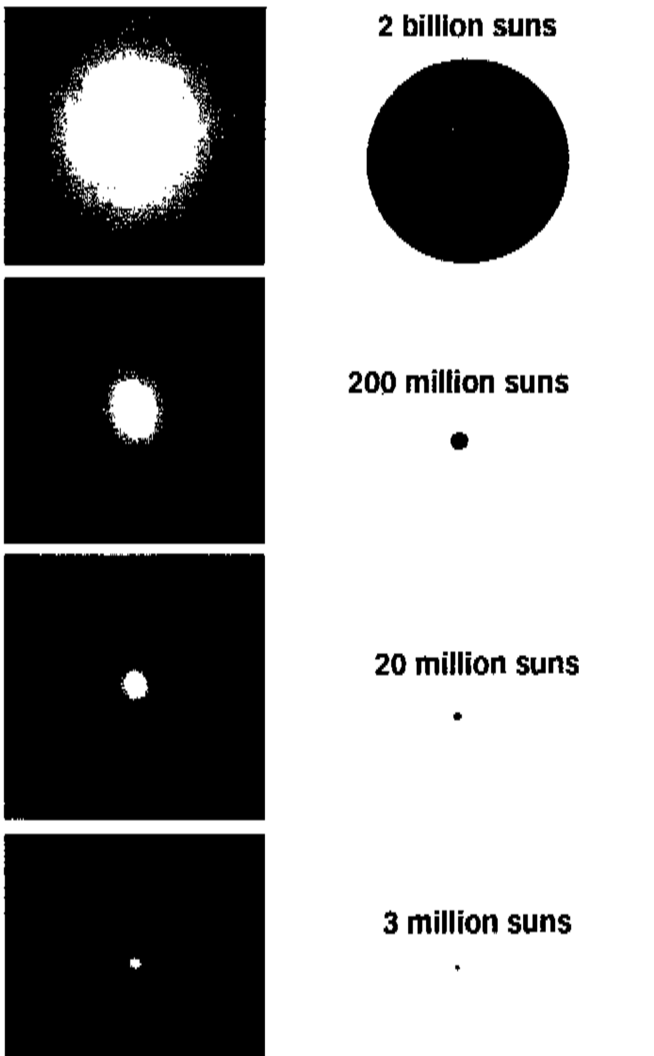
THE HOLE STORY

Black holes may wield an influence far beyond their gravitational reach

BY RON COWEN

Four years ago, astronomer Karl Gebhardt, then a postdoc at the University of California, Santa Cruz, went for a job interview at Harvard University. Although he didn't get the faculty position he sought, he may have gotten something better: a clue that led him to uncover what may be one of the most telling relationships between supermassive black holes and the galaxies in which they reside.



COSMIC LOCKSTEP — A comparison of the cores of four elliptical galaxies (left) shows that the more massive a galaxy's central bulge of stars, the heftier its supermassive black hole (right).

During the Harvard visit, Gebhardt chatted with astronomy professor Avi Loeb about the biggest black holes in the universe—gravitational monsters that lie at the center of galaxies and cram the equivalent of millions to billions of suns into a volume smaller than the solar system. Gebhardt had used the Hubble Space Telescope to determine the mass of several supermassive black holes. Now, he was trying to ascertain whether there was a link between those masses and some more-global property of their home galaxies.

Loeb suggested that Gebhardt compare the mass of each black hole with the average velocities of the billion-or-so stars that surround each hole out to a distance of several thousand light-years. This swarm of stars—a major component of a galaxy—is known as the bulge, and the stellar velocities provide a measure of the bulge's mass.

When Gebhardt made the comparison, he was stunned. Regardless of their size, the bulges always turned out to be 500 times as massive as the giant black holes at the hub of their galaxies. What could be behind this ratio?

Gebhardt wasn't alone in his perplexing finding. Laura Ferrarese, who also studies black holes, had interviewed for the same Harvard job the week before Gebhardt did, and Loeb made the same research suggestion to her. Loeb had also discussed the idea with veteran astronomer David Merritt of Rutgers University in Piscataway, N.J.

Merritt teamed up with Ferrarese, who is now at the Dominion Astrophysical Observatory near Victoria, Canada. They found the surprising correlation between black holes and galactic bulges at about the same time that Gebhardt did.

To understand how puzzling this numeric relationship is, Ferrarese notes, consider that a supermassive black hole can only suck in matter that resides less than a light-year from its own location at the center of a galaxy. Most stars in the bulge, which can lie as far as 20,000 light-years away from the center, aren't in the least affected by the black hole's gravity.

Yet that fixed ratio between the mass of the bulge and the mass of the black hole shows up over and over again in the universe.

"The black hole and the bulge should really not know about each other because they're on completely different scales," notes Ferrarese. "Somehow, something at the very center of the galaxy knows about the overall structure of the galaxy.

"When I started out as a graduate student, supermassive black holes were considered a curiosity . . . relegated to a part of astrophysics that was not connected to anything else," says Ferrarese. Now, they've stolen the spotlight.

LOCKSTEP MODEL The black hole correlation has spurred some 30 theoretical models over the past 4 years, says Gebhardt, now at the University of Texas at Austin. Recent observations, he notes, are winnowing down those theories, giving astronomers a new understanding of how black holes influence the growth and evolution of galaxies.

The correlation suggests that galaxies and black holes have grown in lockstep—at least for the last few billion years of cosmic history. One model of this coevolution harks back to work described

GEBHARDT/NASA

in 1998 by Martin Rees of the University of Cambridge in England, and Joe Silk, now at the University of Oxford in England.

A galaxy starts out as a big cloud of gas. As gas sinks toward the center of a fledgling galaxy, notes Silk, "the natural thing is that a big black hole forms and it grows." It feeds on the rain of material falling into it.

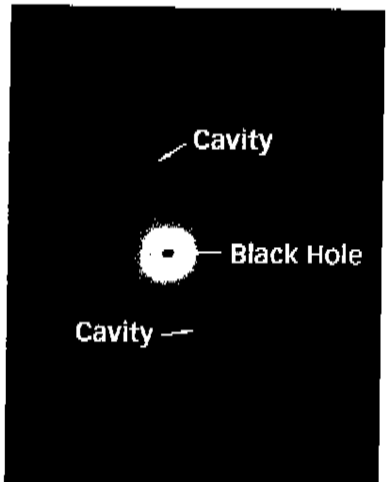
Supermassive black holes could have a profound influence on their galaxies, Silk and Rees surmised, because they spew vast amounts of energy in the form of radio jets, quasar beams, and intense winds. These energy blasts propagate thousands of light-years from the black hole, beyond its gravitational reach and well into the region where stars in the bulge are made.

The energy a supermassive black hole pours out may put it in command, determining how rapidly and to what extent its host galaxy forms stars from clouds of gas.

"Our idea was that the jets would initially accelerate the formation of stars, by compressing the gas," Silk says. But the more material the black hole pulls in, the more powerful the jets and radiation that it expels.

"As the outflow becomes more and more intense, it would blow the remaining gas away," Silk says. Without gas, star formation would cease, and the black hole would have nothing to feed on. "When you've gotten rid of all the gas, that's the end," he says.

Silk and his colleagues calculate that no black hole can become heavier than about 3 billion times the mass of the sun. The largest supermassive black hole ever detected, at the center of the elliptical galaxy M87, weighs in at just this value.



DARK INFLUENCE — Two giant cavities in the galaxy cluster MS 0735.6+7421 have been hollowed out by an eruption from a supermassive black hole. The ongoing eruption, depicted in this illustration, has already expelled material in an amount equivalent to a trillion suns and greater than the mass of all the stars in the Milky Way.

M. WEISS/CXC, NASA

Self-limitation of black hole growth may also account for the puzzlingly brief lifetime of quasars, the brilliant cosmic beacons powered by supermassive black holes, assert Loeb and Stuart B. Wyithe of the University of Australia in Melbourne. In several upcoming articles in the *Astrophysical Journal*, the researchers suggest that a quasar lasts only a few tens of millions of years because during that period, its supermassive black hole blows away the gas supply that fuels the hole and sustains the cosmic beacon.

In the Jan. 6 *Nature*, Brian McNamara of Ohio University in Athens and his colleagues report that a supermassive black hole may have created the most powerful eruption ever recorded in the universe. The team found evidence of the eruption when they used the Chandra X-ray Observatory to examine hot gas in the cluster of galaxies called MS 0735.6+7421. Two enormous cavities extend away from the black hole housed in the cluster's central galaxy, they say.

Over a distance of a million light-years, jets from this supermassive black hole appear to have pushed out as much gas as is contained in a trillion suns. The eruption has already released hundreds of millions of times as much energy as is contained in a gamma-ray burst, the most violent type of explosion that scientists had previously detected.

A black hole's jets and winds may also explain an emerging puzzle about galaxies in the early universe, says Silk. Astronomers are finding an abundance of galaxies that were already in place when the universe was just 1 billion to 2 billion years old.

The light now reaching Earth from these galaxies carries information about their infancies. Surprisingly, the galaxies are populated with mature, reddish stars typical of galaxies billions of years older *(SN: 3/1/03, p. 139)*.

"You'd think everything in the early universe would be young," notes Silk, but many galaxies seem to have matured in a relatively short time after the Big Bang.

Supermassive black holes might explain the apparent paradox. Silk suggests that the jets and radiation pouring out of supermassive black holes put these early galaxies into overdrive, speeding up star formation (*see box*).

"Imagine a cold, dark gas cloud sitting in a new galaxy," says Silk. There isn't yet a star in the cloud, but suddenly a wind of hot gas from a black hole in the center sweeps by. As Silk sees it, the

In the Beginning: How to Grow a Black Hole

Merger or acquisition?

The recent finding of supermassive black holes already in place soon after the Big Bang raises the question: How could these heavyweights have had time to form? Assuming that black holes weren't forged in the Big Bang itself, they likely arose from the gravitational collapse of the first stars in the universe. Several properties of this first generation of stars would have favored the rapid and early formation of black holes, says Piero Madau of the University of California, Santa Cruz.

Studies by several research groups suggest that the first stars were unusually hefty—about 100 times as heavy as a typical star today—and that they blazed into existence when the cosmos was only about 200 million years old. These heavyweight stars were much better at holding onto their girth than were later generations of massive stars, which have fierce winds that blow away much of the material they were born with.

When heavy stars undergo a final gravitational collapse, they can form black holes weighing as much as 200 times the mass of the sun.

To pack on more material, these baby black holes could have taken either of two routes, says Joe Silk of the University of Oxford in England. In one scenario, a black hole becomes bigger by simply pulling in gas from its surroundings, a process known as accretion. In another model, black holes get heftier when their host galaxies collide and merge. The mergers presumably cause the central black holes within each of the colliding galaxies to coalesce.

Silk notes, however, that the merger of two galaxies doesn't always lead to a new black hole partnership. The two gravitational beasts must get considerably closer than a light-year—near enough for their mutual gravity to bind them together. Otherwise, two lower-mass black holes would persist in the galaxy instead of a single really big one at the center.

Observations now under way or in the planning stages should help determine whether black holes grow primarily by accretion or merger, Silk says. One strategy notes that, unlike the slow accretion of gas, mergers are violent processes that unleash a torrent of gravitational waves. These disturbances propagate as ripples in space-time. Future gravitational-wave detectors, including an array planned for launch next decade, should have the sensitivity to find evidence of every sizable merger, says Silk. —R.C.

extra pressure from this wind would cause the cloud to collapse, triggering unexpectedly early star formation.

COSMIC CHICKEN AND EGG This model, in which black holes pour energy back into their host galaxy, may also answer a much-debated chicken-and-egg problem: Which came first, supermassive black holes or the star-filled galaxies that surround them?

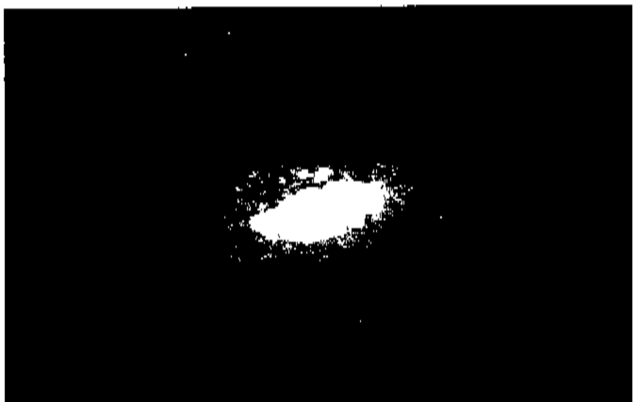
Some astronomers have proposed that most of a galaxy's stars would have to have formed before there'd be enough material available to produce a supermassive black hole. But for Gebhardt, the answer is clear: Black holes came first. The stars would begin forming in abundance only after black holes had spewed radiation and pressure waves into a galaxy's clouds of gas.

If this scenario holds true, Gebhardt says, then early in the universe, the relationship that he and the Ferrarese-Merritt team first noted between the mass of a black hole and the mass of the stars wouldn't have had enough time to be established. In these early galaxies, a black hole would take up a much larger proportion of the galaxy's mass, and the bulge of stars would get a smaller share.

That's just what astronomers are finding in a few galaxies that date back to about 1 billion years after the Big Bang.

For example, Fabian Walter of the Max Planck Institute for Radio Astronomy in Bonn, Germany, and his colleagues recently used the Very Large Array of radio telescopes near Socorro, N.M., to examine one of these most-ancient galaxies. The galaxy, dubbed SDSSJ1148+5251, houses the most-distant quasar known.

The researchers couldn't directly study the stars in the bulge of the galaxy because their light is lost in the glare from the quasar. But by measuring the motion and extent of gas around the quasar, Walter's team estimated that the total mass of the galaxy is about 50 billion times that of the sun. The bulge of the galaxy must therefore weigh less than this amount.



GALACTIC MONSTER — Supermassive black hole at the center of the galaxy VCC1250, located in the Virgo cluster of galaxies.

ACSVCS TEAM, NASA

Fifty billion suns is a lot of matter, but multiplying the measured mass of this galaxy's supermassive black hole by 500, in accordance with the ratio determined for galaxies later in the universe, gives a far bigger mass. The black hole "should be surrounded by a stellar bulge of several trillion solar masses," says Walter.

The discrepancy provides evidence "that the black hole forms before the stellar bulge," Fabian says. In this case at least, the black hole formed before most of the stars in the galaxy had a chance to do so.

Over the past 30 years, as astronomers have struggled to understand how galaxies grow and evolve, black holes have been given short shrift, says Gebhardt. "Black holes just weren't even considered" to play a role in the growth of galaxies, he says, because "they were thought just to be a by-product of the galaxy and have such a small mass."

"But now what we're finding is that not only does every galaxy have a black hole, but it appears to have a significant influence on the evolution of the galaxy." ■