A beast in the core
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A BEAST IN THE CORE

Supermassive black holes probably lurk in the centers of all the big galaxies.

by Marcia Bartusiak

HERE'S NO STOPPING A DETERMINED astronomer. More than 30 years ago, when quasars were still a complete mystery, observers went to extraordinary lengths to learn their secrets. In 1963 Australian radio astronomers even cut down trees and tipped a weighty radio dish beyond its safety limits to pinpoint the radio signal of a quasar caught low on the horizon. It was 3C 273, which in the optical turned out to be a star-like object. After analyzing its spectrum, Caltech astronomer Maarten Schmidt realized that 3C 273 was not a star at all, but rather an ultraluminous object situated some two billion light-years away. By today's standards, that's relatively close by for a quasar — most are now found more than 10 billion light-years distant.

The Hubble Space Telescope is currently revealing quasars in startling detail. Where once astronomers saw only dots of light, they now see the glowing compact cores of far-off galaxies, each core pouring out the energy output of a staggering 100 galaxies crammed into a volume of space the size of the solar system. Some quasars appear to have been triggered by an interaction or collision with another galaxy. Other quasars, however, reside in relatively normal galaxies.

Exactly how a quasar turns on is still being debated, but most theorists agree it probably involves a humongous black hole, one that contains the mass of a million to ten billion suns. The black hole gravitationally attracts nearby matter and never lets it go. But before the material is permanently captured, it gathers into a swirling accretion disk that surrounds the black hole and radiates intensely. It's thought the black hole itself spins, like a giant magnetic dynamo, producing two jets of subatomic particles that shoot away in opposite directions from each pole at near the speed of light. All of this activity occurs as long as there is enough fuel nearby — stars, dust, and gas — to feed the dark monster in the middle.

Astronomers would love to observe this process more closely, but glare and distance effectively hide such awesome engines from prying astronomical eyes. It's like trying to examine the workings of a searchlight when it's beaming into your face. In recent years, though, a new line of study is finding a

A monster black hole probably lurks in the core of every major galaxy, including our own. Some of these black holes, as shown in this painting, power jets of subatomic particles that travel across hundreds of thousands of light-years at near light speed. *Astronomy:* Adolf Schaller

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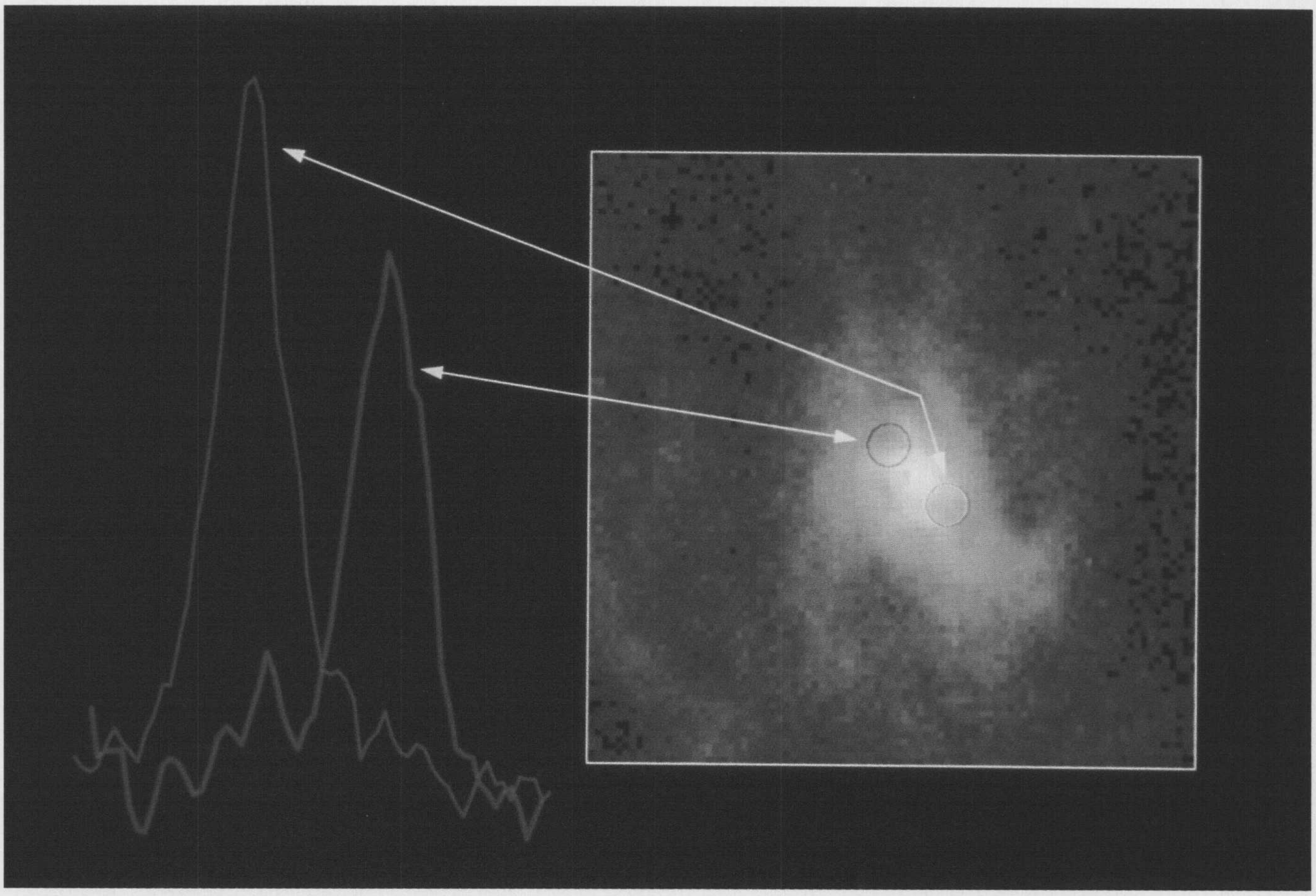

Holland Ford (Johns Hopkins University), et al., and NASA

The Hubble Space Telescope has imaged a gaseous disk (above) in the core of the giant elliptical galaxy M87. One side of the disk is highly blueshifted, meaning the gas is moving toward Earth at very high speed, while the other side is highly redshifted, meaning the gas is moving away from Earth at very high speed. The gas must be whipping around a central supermassive object — most likely a two-billion-solar-mass black hole. M87's black hole powers a humongous jet (right), a relic of the quasar epoch.

way around that obstacle. You might call it "quasar paleontology": the study of quasars by examining the fossils that presently surround us. "They're now old and dead," notes University of Michigan astronomer Douglas Richstone, "but we can still learn from them." The closest quasar fossil, a relatively quiescent black hole of some two million solar masses, resides smack dab in the center of our own Milky Way Galaxy. Indeed, astronomers are coming to believe that every major galaxy was a quasar in its youth. Quasar activity is likely a common phase in the life of a galaxy and not the exception, as once thought.

The search for quasar fossils began in the late 1970s. Caltech astronomers Peter Young and Wallace Sargent figured that if quasars had truly been powered by black holes, the remnants should be scattered all about us. To check, they peered into the center of M87, the giant elliptical galaxy that sits at the center of the great Virgo cluster of galaxies located some 50 million light-years away. As a prominent radio source, M87 was a good prospect. Young and Sargent soon claimed they found evidence for a three-billion-solar-mass black hole in M87's center. Other astronomers were skeptical.

But Young and Sargent's work was highly influential, for an important paradigm was at stake here. The most persuasive way to explain the tremendous energies spewing from quasars is a black-hole engine. Alternate sources of energy — supernova explosions, extreme star birth, and such — fall far short. "The success of the black-hole picture strongly motivated us to look for dead engines," says University of Hawaii astronomer John Kormendy. "But it's a tricky and dangerous subject. It's easy to talk yourself into believing that you've proved what you expect to find." The hunt was vigorously renewed ten years ago, especially as electronic instrumentation and telescopic resolution improved.

Richstone, noted for his modeling of stellar orbits within a galaxy, first got involved via a letter. Alan Dressler of the Carnegie Observatories sent him data on both M31, the nearby Andromeda Galaxy, and its smaller companion M32. Did the unusually rapid motions he was detecting within the Andromeda Galaxy's center, asked Dressler, suggest that stars were swiftly orbiting a supermassive black hole? Richstone concluded they did. The breakneck speeds were hard to explain if you assumed that the center was populated by a dense cluster of low-mass stars or stellar remnants, the only other viable alternatives.

Kormendy independently reached an identical conclusion. Both groups estimated that the Andromeda Galaxy harbored a black hole weighing about 30 million solar masses, while M32 had a black hole a tenth that size. Kormendy, the world's most prolific black-

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hole hunter, would go on to find half a dozen more quasar fossils in galaxies ranging out to the Virgo cluster. His telescope, the 3.6-meter Canada-France-Hawaii Telescope located atop Hawaii's Mauna Kea, provided him the superb seeing conditions he needed to carry out the painstaking measurements required in this line of work.

The technique for finding a massive black hole in a galaxy's center — at least indirectly — is based on fundamental laws of physics. Think of a satellite orbiting the Earth. If you measure the radius of the satellite's orbit and its speed, Newton's laws of gravity allow you to figure out Earth's mass. Similarly, by measuring a star's speed and orbital size within a galaxy, you can determine the mass inside the star's orbit. A black hole is suspected when astronomers see stars and gas zipping around extremely fast near the center; in many cases, only a supermassive black hole can keep such high-velocity stars from flying out of the galaxy.

At first, black-hole hunters tackled the easiest cases: nearby spirals with disks seen edge-on, such as M104, the famous Sombrero Galaxy. Candidates need to be close by so astronomers can resolve the tiny region in the middle where the black hole affects the motions of the inner population of stars, about one percent of the mass of the galaxy. Edge-on is the best orientation to measure stellar orbital speeds, as one edge of the disk spins toward us, and the other spins away. Kormendy found a billion-solar-mass black hole within M104 in this way. Another good case is NGC 3115, which likely contains a two-billion-solar-mass monster.

Soon after the Hubble Space Telescope was repaired in 1993, many astronomers teamed up to continue their explorations from space. Since their targets were galactic nuclei, these Hubble observers soon nicknamed themselves the "nukers." Hubble speeded up the process and quickly added to the count. Indeed, every galaxy that Hubble has closely examined reveals a central black hole.

Such was the case for NGC 4261, a giant elliptical galaxy. By focusing Hubble on that target, Johns Hopkins astronomer Holland Ford and colleagues were able to vividly image an 800-light-year-wide disk of gas and dust that is likely fueling a black hole a billion times the mass of the sun. This case is particularly important because NGC 4261 is still active (although not at quasar levels). Enormous jets of radiation are emerging from the core. The galaxy's central black hole will probably be feeding on its "meal" for some 100 million years, a common lifetime for many active galaxy outbursts.

Another spinning gas disk was found by Hubble in M87, the original quasar fossil candidate. With a jet that is visible to both radio and optical telescopes, M87 is widely regarded as a former quasar that gently hums along. Along with NGC 3115, Kormendy believes it's one of the best cases for a quasar fossil so far.

Radio astronomers introduced the newest technique for hunting down quasar fossils. Using a network of radio telescopes that span the continent, they tracked the intense microwave signals emitted by water masers, vast clouds of water molecules whipping around the center of the dust-shrouded spiral galaxy M106. This opens up the opportunity to look into dusty galaxies that are opaque to optical telescopes.

Tod Lauer (NOAO), Sandra Faber (UCSC), and NASA

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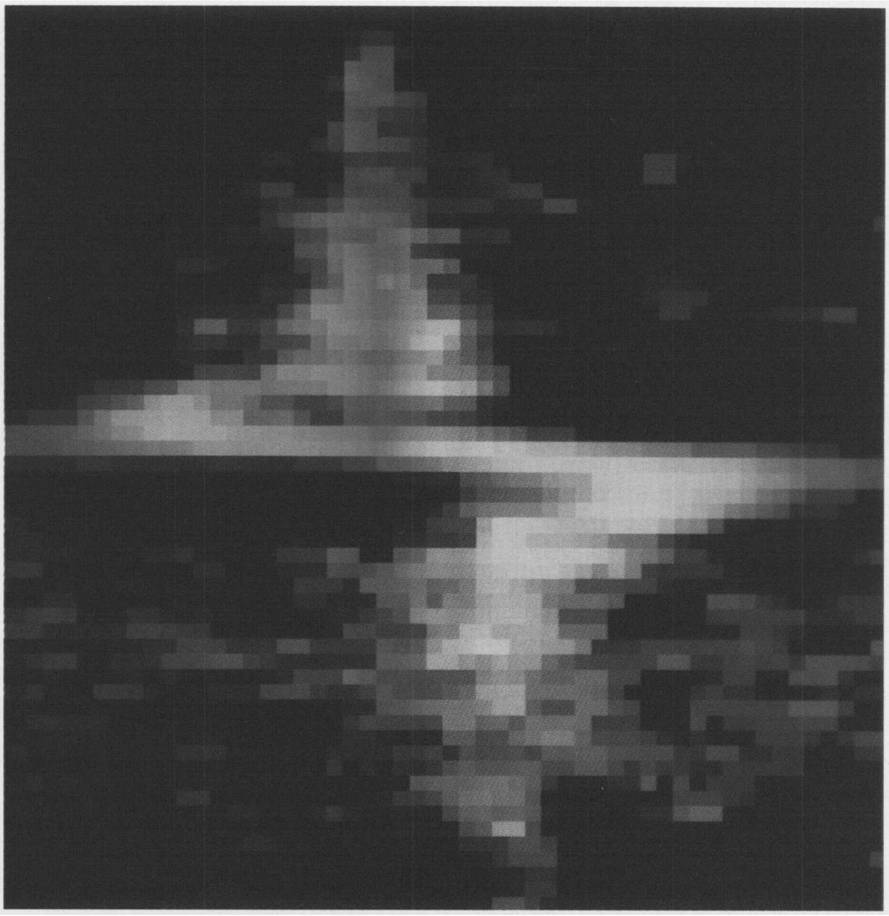


Gary Bower, Richard Green (NOAO), et al., and NASA

The Hubble Space Telescope's new STIS instrument catches the telltale signature of a monster black hole in the core of elliptical galaxy M84: a sharp zig-zag of blueshifted and redshifted gas. Gas just 25 light-years from the core is swirling around a central mass at 900,000 miles per hour, indicating a black hole of 1.5 billion solar masses.

All the differing techniques appear to be agreeing on the mass of the black holes in each galaxy. "That's very encouraging," says Kormendy. All in all, about 15 bona fide quasar fossils have been found so far; another two dozen are suspected from cruder measurements. "Ten years ago, if you found an object that you thought was a black hole in the center of a galaxy, half the field thought you were a little nuts," says Richstone. "I think that attitude was fair: Extraordinary claims demand a high level of proof. It was reasonable for people to be skeptical, but now we've gone from the simple discovery stage to carrying out surveys and demographics."

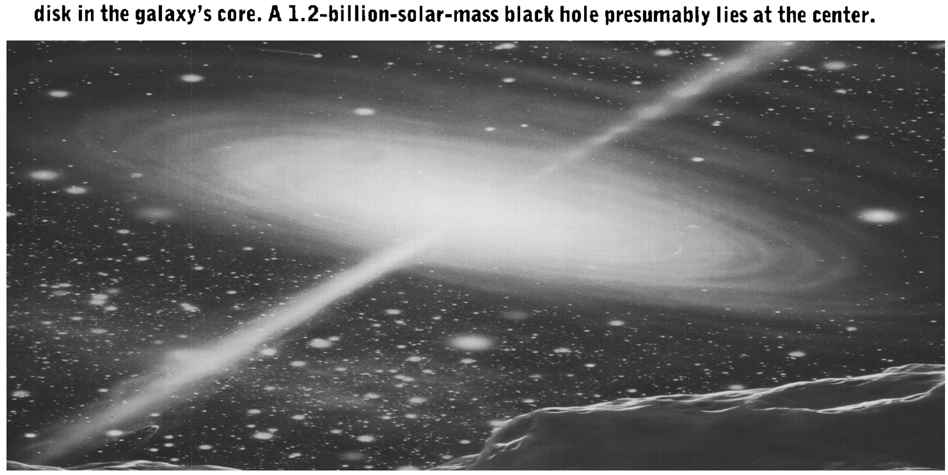
Working with Maarten Schmidt on several quasar surveys during the 1970s and 1980s, Richard Green had suspected that the quasar phenomenon was a short-lived episode in nearly all galaxies. "It's like a Roman candle — a burst of brightening for a relatively brief period," explains Green, now deputy director of the National Optical Astronomy Observatories in Tucson, Arizona. But it was also possible that only a fraction of all galaxies — a special breed — experienced an episode of quasar activity for a longer time. Now, though, the ever-expanding list of quasar fossils is encouraging astronomers to believe that Green's initial suspicion is correct: that nearly all major galaxies — spirals and ellipticals alike — harbor supermassive black holes, former quasar engines. With fossils littering the celestial sky, quasars now seem rather common.

"Now I want to know the exceptions," says Green. Kormendy has found at least one so far; spiral galaxy M33, a tiny neighbor of Andromeda, is devoid of a bulge and appears to have no supermassive black hole at its center, at least as observed so far. This suggests that supermassive black holes are connected to the presence of a bulge.

The more astronomers locate these fossils, the more they are able to discern patterns. Already, Kormendy and Richstone have discovered a fascinating rule: The greater the mass of the elliptical or spiral bulge, the larger its central black hole. "That's an astonishing fact," says Richstone. "Somehow, when the black hole forms, it knows what kind of galaxy it's in. Or when a galaxy forms, it knows what kind of black hole is in it." This seems to suggest that the formation of a galaxy and the growth of its central black hole are intimately linked in some as yet undetermined way. "It used to be only a theory — that black holes served as the 'engines' for quasar activity," says Kormendy. "But now we've established that black holes are indeed the engines and that they have masses as predicted."

This is an exciting find because it offers a means of determining how these black holes formed in the first place. Perhaps the black holes formed first, serving as "seeds" around which

A ground-based optical and radio composite image (left) shows a jet streaming out of the center of elliptical galaxy NGC 4261. A Hubble image (right) shows a 400-light-year-wide disk in the galaxy's core. A 1.2-billion-solar-mass black hole presumably lies at the center.



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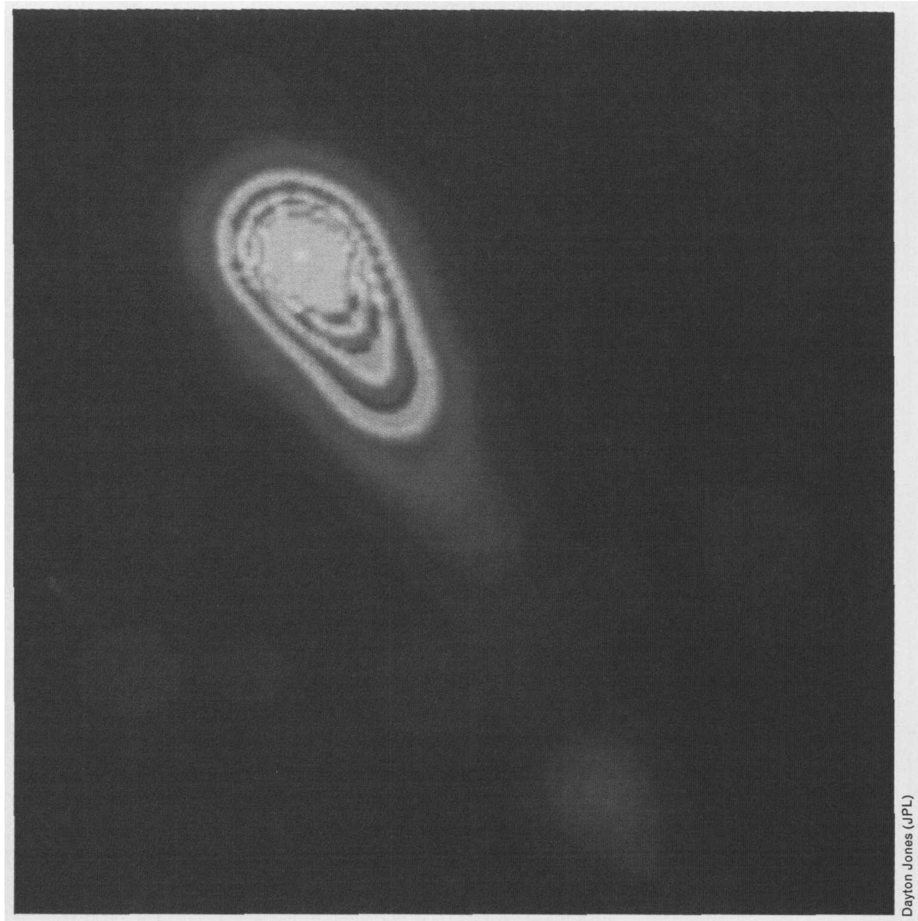

Dayton Jones (JPL)

This radio image shows a powerful jet shooting out of the core of galaxy NGC 6251. Later Hubble Space Telescope observations strongly suggest this galaxy harbors a supermassive black hole.

galaxies formed; over time, the black holes consumed the galaxies' stars and gas to enlarge themselves. Or perhaps there were smaller black holes, each in a galactic building block, that eventually merged to form a giant galaxy as well as a supermassive black hole. For now, there's not enough evidence to distinguish between the two scenarios.

Can astronomers truly be sure that these black holes are linked to past quasar activity? The numbers are tantalizingly suggestive. The density of galaxies with supermassive black holes observed here in our local surroundings just about matches the density of quasars seen in the far universe. "We can see the light emitted from quasars in the distant past, and we can estimate the density of quasar relics required in the present universe to make that light," says Richstone. "The answer turns out to be very close to the black holes we are discovering. It's that fact that makes us believe we're seeing the relics of old quasars."

ut there's a major puzzle left to solve: Some of these galaxies seem to have lots of "food" remaining in their center. Why do they stay inactive in the midst of this cornucopia? "This could be embarrassing," reported Kormendy and Richstone in a review of the field. New theoretical studies, however, are suggesting that the disks of material actually remain quiet most of the time and only flare up when an instability occurs. Perhaps conditions for a runaway catastrophe — a quasar outburst — are best in the early universe, when the cosmos was smaller and when galaxies were young, gas-rich, and more liable to bump into one another.

An instrument called STIS (for Space Telescope Imaging Spectrograph), recently installed on Hubble, will surely accelerate the discovery of more fossils. One of its first measurements showed its astounding abilities. As soon as it was operative in January 1997, according to STIS team member Green, NASA officials told them to "go find us a new black hole." "And we aimed to please," jokes Green.

Gary Bower, Green's colleague at the NOAO, had already been studying M84, an elliptical galaxy with shadowy dust lanes, perhaps the remnant of a galaxy recently gobbled up. It was a promising subject but awkwardly placed in the sky. The astronomers had only one good guide star to keep Hubble steady. Nevertheless, the data on M84's inner core, originally gathered to check that STIS was in working order, revealed stunning science.

The spectrum, a colorful "zigzag," is a compelling signature of a black hole. "We first see a very slow rotation in an outer, larger gas structure," explains Green. "Then, suddenly, as we approach the center, the gas velocities go faster and faster and faster. Right in the center, there's a huge spread. The top velocity is 400 kilometers per second, very fast for material in a stable orbit within 25 light-years of the galaxy's center." This implies that within that disk lies a gigantic black hole containing the mass of 1.5 billion suns.

Black-hole hunters have been eagerly anticipating STIS. It can carry out a detection 40 times faster than an earlier Hubble instrument, the Faint Object Spectrograph. The FOS had to take data spot by spot, slowly building up a complete sample across the galactic center. STIS does it in one fell swoop. The nukers will soon use STIS to examine ten more galaxies, all good fossil candidates. "We're now in high gear," says Kormendy. With STIS in place, new finds will likely arrive fast and furiously. In the past, Kormendy has spent a full year piecing together the model for just one galaxy. "But we now have a level of confidence we didn't dare have before," he says.

Black holes, once a theoretical curiosity, seem to be central features in every large galaxy in the universe. No longer oddities, they may be the natural result of galactic evolution and perhaps engines for tremendous fireworks displays that announce each galaxy's birth. "I showed our work to a stellar astronomer, a former black-hole doubting Thomas," notes Green, "and she said, 'I guess I'm going to have to start believing in this.'" ■

Award-winning science writer Marcia Bartusiak is a member of Astronomy's *editorial advisory board. Her last article was "Cosmic Jekyll & Hyde" in the May 1998 issue.*

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