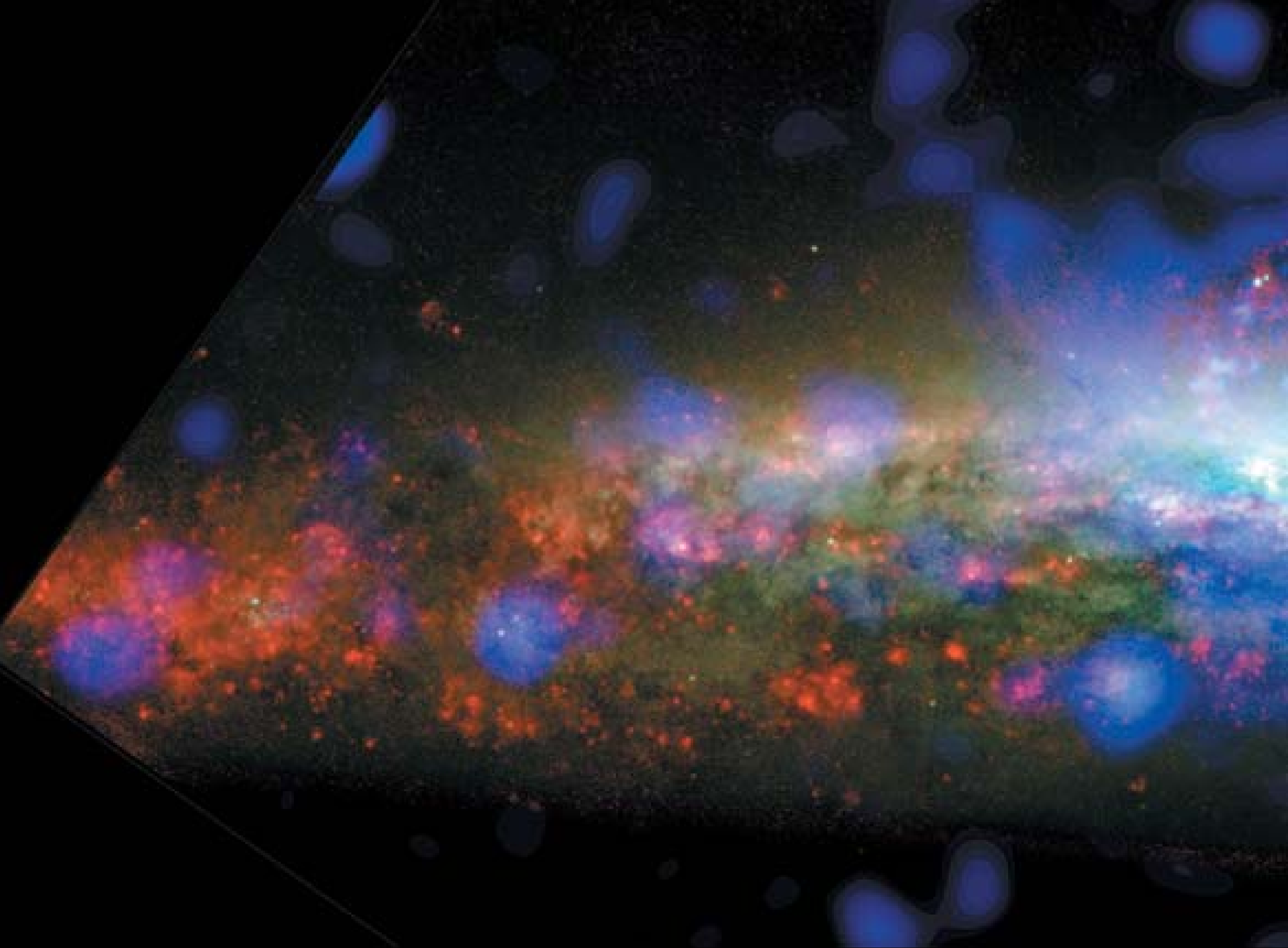
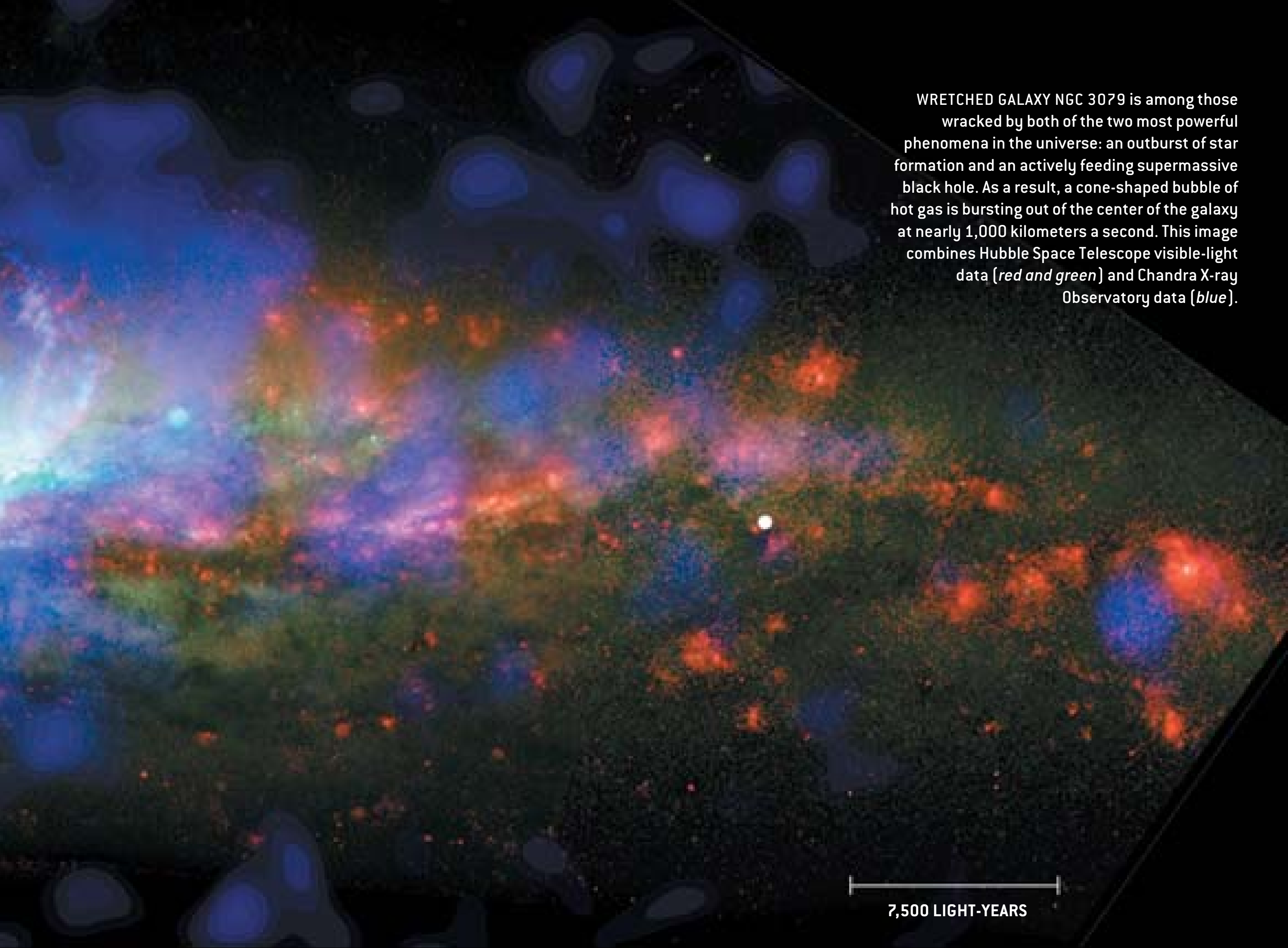


The Galactic

Why do GIANT BLACK HOLES and STELLAR BABY BOOMS, two phenomena with little in common, so often go together?

BY KIMBERLY WEAVER



WRETCHED GALAXY NGC 3079 is among those wracked by both of the two most powerful phenomena in the universe: an outburst of star formation and an actively feeding supermassive black hole. As a result, a cone-shaped bubble of hot gas is bursting out of the center of the galaxy at nearly 1,000 kilometers a second. This image combines Hubble Space Telescope visible-light data (*red and green*) and Chandra X-ray Observatory data (*blue*).

Odd Couple

Black holes have a bad reputation. In many ways, it is deserved.

They are the most efficient engines of destruction known to humanity. Their intense gravity is a one-way ticket to oblivion for anything that strays too close; inside them is undiscovered country from whose bourn no traveler returns. We see them only because the victims do not go quietly to their doom. Material spiraling into a black hole can heat up to millions of degrees and glow brightly. Some of its kinetic energy and momentum may be transferred to a jet of particles flowing outward at close to the speed of light. Black holes of varying sizes take the rap for fusillades of radiation and plasma that astronomers observe all over the cosmos.

Yet black holes are not all-powerful. Even those found at the centers of many galaxies, supermassive black holes—whose very name connotes a voracious monster that rules its galactic roost—are minuscule by cosmic standards. They typically account for less than a percent of their galaxy's mass, and their gravity is highly concentrated. Accordingly, astronomers long assumed that supermassive holes, let alone their smaller cousins, would have little effect beyond their immediate neighborhoods. Star formation farther out in the galaxy was thought to march to the beat of a different drummer.

So it has come as a surprise over the past decade that black hole activity and star formation are closely intertwined. In many galaxies where black holes devour material greedily—generating a phenomenon that astronomers call an active galactic nucleus (AGN)—stars form at a precipitous rate in episodes known as starbursts. How can these two seemingly disconnected processes be so intimately related?

Today the AGN-starburst connection is a revolutionary area of research. Beautiful Hubble Space Telescope images are allowing astronomers to pick apart the complex events at the hearts of galaxies, the Chandra X-ray Observatory is peering into places hidden to Hubble, and theorists are trying to make sense of it all. This research bears on some of the most basic questions in astronomy: How did the dark early universe come to light up with billions of stars? Did supermassive black holes need a helping hand to grow to be so big? Could they be agents of creation as well as destruction?

Galaxies on Steroids

BOTH ACTIVE GALACTIC nuclei and starbursts are among the most spectacular phenomena in the universe. An AGN is a luminous and compact source of light at the center of a galaxy. Quasars are the most extreme example. Pumping out as much power as a billion to a trillion suns, AGNs can outshine the rest of their host galaxies. The supermassive black holes that are thought to power them pack a million to a billion times the sun's mass inside a region smaller than a thousand times the sun's diameter. Like a falling rock, material spiraling toward the hole picks up speed and releases energy as it collides with other material. In so doing, it gives off radiation at all wavelengths: radio, infrared, optical, ultraviolet, x-ray, gamma-ray.

Starburst galaxies rival the brilliance of AGNs. They are places where gas condenses into stars at a rate equivalent to producing up to 1,000 suns a year—1,000 times faster than stars currently form in our own galaxy. Some starbursts are confined to comparatively small regions, only hundreds of light-years across, located near the center of a galaxy; others occur on much larger scales, sometimes tens of thousands of light-years across. Starbursts often take place in galaxies that are going through, or have recently undergone, a close encounter or merger with a neighboring galaxy. The tidal forces between the two galaxies disrupt gas and cause it to fall inward, greatly accelerating the normal process by which interstellar clouds collapse and form stars. A starburst typically lasts about 10 million years before running out of gas (literally).

Like AGNs, starburst galaxies shine at a wide range of wavelengths. Much of their power output is simply the light of the stars that have been formed. Starbursts tend to be especially bright sources of infrared radiation, which is produced when interstellar dust absorbs and reradiates starlight. Starbursts also produce a lot of x-rays, which pour forth from massive stars, especially as they die. A massive star goes out with a bang: a supernova explosion, which generates x-rays directly, scatters hot x-ray-emitting debris, and leaves behind a neutron star or a smallish black hole, capable of cannibalizing a companion star and spewing x-rays. The surrounding interstellar gas, heated by all the stellar activity, gives off x-rays, too.

The idea that AGNs are somehow linked to starbursts was not sparked by a single earthshaking discovery but has evolved slowly. It goes back to a time when astronomers were still debating what powered AGNs. Although today nearly all attribute AGNs to supermassive black holes, the situation was not so clear as recently as 15 years ago. Researchers including Roberto Terlevich of the University of Cambridge and Jorge Melnick of the European Southern Observatory argued that AGNs were a type of starburst. To the telescopes of the day, a tight knot of young stars and supernova debris would look just like a supermassive black hole.

Overview/*AGNs and Starbursts*

- The two most powerful phenomena in galaxies are active galactic nuclei (AGNs) and starbursts. The former are intense, concentrated sources of light—probably matter falling into a supermassive black hole. (Quasars are the best-known example.) Starbursts are galactic fireworks shows during which stars form at a frenetic pace.
- Astronomers used to think that AGNs and starbursts, which are often separated by vast distances, had nothing to do with each other. But they have found that the two phenomena tend to occur hand in hand.
- Does an AGN cause the starburst? Or vice versa? Or are they both caused by some underlying process? The answer will be crucial to understanding the evolution of galaxies.

The Case for a Connection

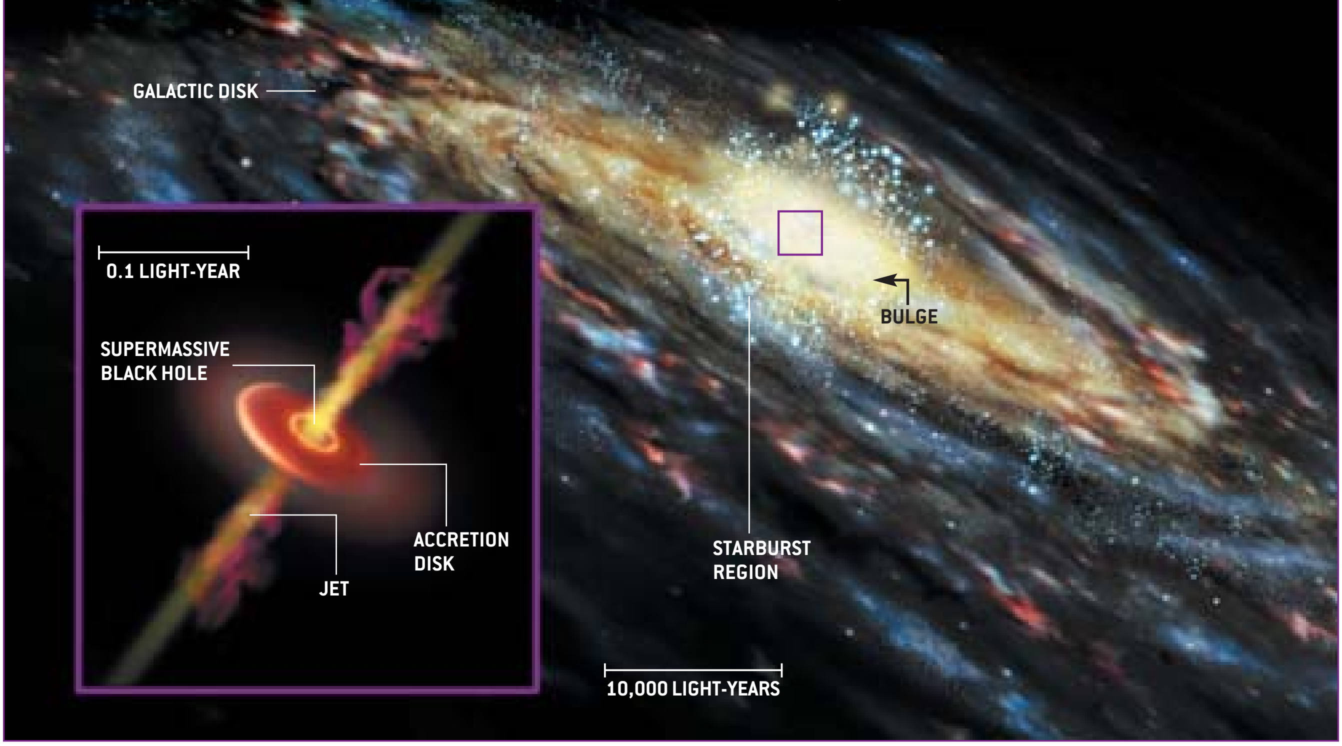
THE NOTION FELL FROM FAVOR only in the late 1980s, as higher-resolution telescopes operating at multiple wavelengths began to reveal just how compact AGNs are: at most a few light-years across and probably a matter of light-minutes across, far too small to encompass a starburst. Even if an entire cluster of stars could fit into such a small space, the stars would rapidly merge together and collapse into a black hole anyway. In addition, AGNs tend to be accompanied by fast-moving jets of material—as a black hole, but not a starburst, would naturally produce [see "Black Holes in Galactic Centers," by Martin J. Rees; SCIENTIFIC AMERICAN, November 1990].

Although AGNs and starbursts proved to be distinct phenomena, these discussions primed astronomers to accept that they might be related in some way [see "Colossal Galactic Ex-

NASA/CXC/GERALD CECIL *University of North Carolina (preceding pages)*

ANATOMY OF A GALAXY

A TYPICAL SPIRAL GALAXY contains 100 billion stars, most in a flattened disk. Toward the center is a bulge of stars, and at the very center is usually a supermassive black hole. If the hole is actively feeding, infalling matter forms an accretion disk or is shot back out as a jet. If the galaxy is undergoing a starburst, loose gas turns into stars at a high rate. For years, astronomers thought that the hole and the starburst were unrelated. They were wrong.



plosions," by Sylvain Veilleux, Gerald Cecil and Jonathan Bland-Hawthorn; Scientific American, February 1996]. Several pillars of observational evidence now point to just such a relation. The findings come in a bewildering variety, suggesting that the connection has had a pervasive effect on the universe.

The first piece of evidence is the most direct. Telescopes have seen AGNs alongside starbursts in nearby galaxies. These observations have been tricky to make because galactic cores are filled with gas and dust, obstructing our view. This is where x-ray astronomy comes in. X-rays can penetrate dense gas. Even though current x-ray telescopes lack the resolution of Hubble, they often produce clearer pictures of the dusty centers of galaxies.

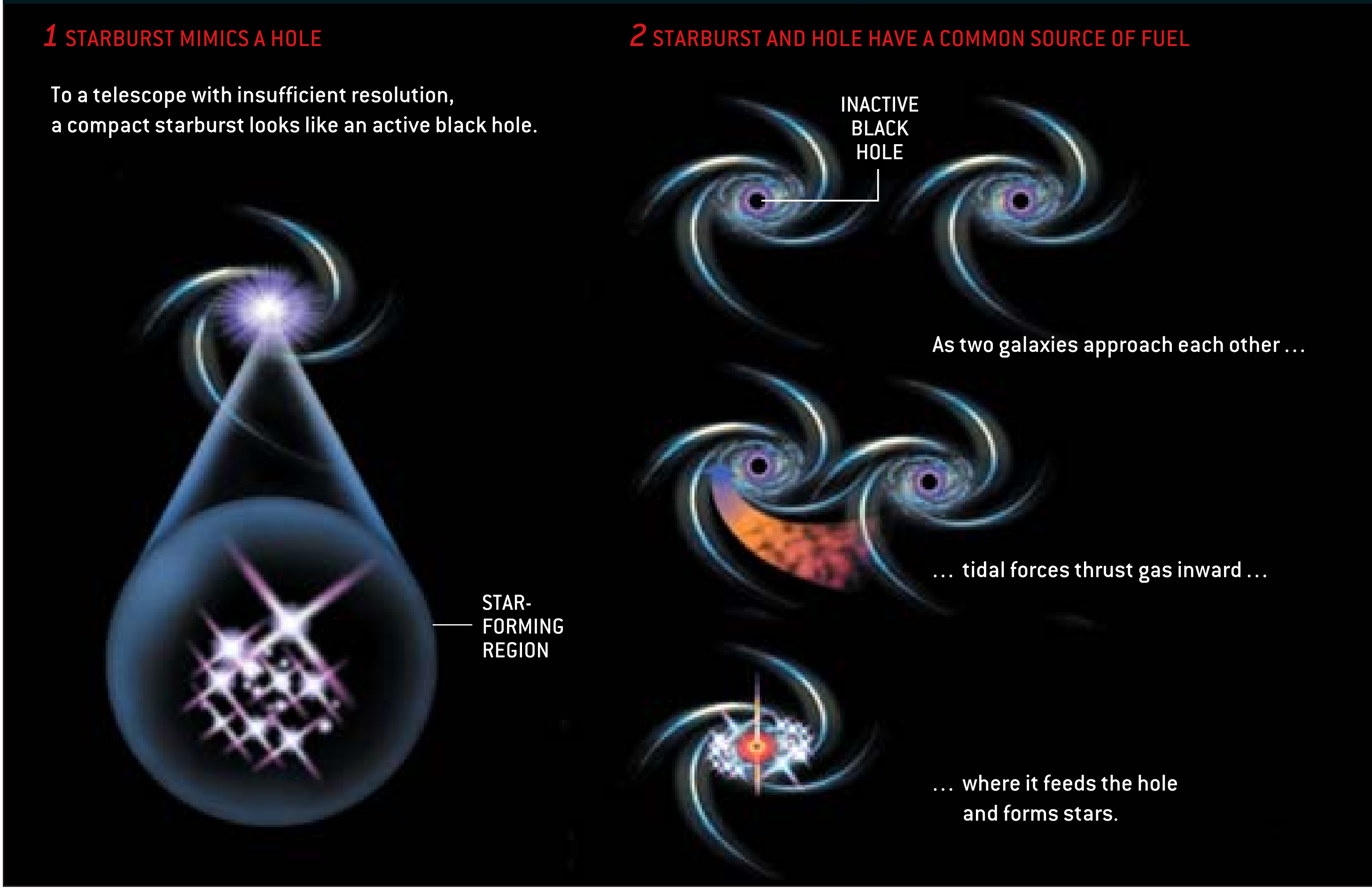
A second line of evidence comes from a recent survey of nearly 23,000 AGNs by Timothy Heckman of Johns Hopkins University and his colleagues. Rather than scrutinize images of all those galaxies, the researchers inferred the presence of AGNs or starbursts from the strength of particular spectral lines, taking highly ionized oxygen as a sign of an AGN and strong hydrogen absorption as indicative of a starburst. The main conclusion was that galaxies with powerful AGNs had many more young stars than did similar galaxies without AGNs. The more powerful the AGN, the more likely it was that the galaxy had experienced a major starburst not long ago. In short, this study verified that the AGN-starburst connection is not merely anecdotal.

Third, AGN galaxies are not the only ones to be blessed with supermassive black holes. Astronomers have detected them at the centers of inactive galaxies as well. It seems that giant holes are everywhere. Most of the time, they lie dormant and invisible; they produce AGNs only when material falls into them at a large and sustained rate. John Kormendy of the University of Texas at Austin, Douglas O. Richstone of the University of Michigan at Ann Arbor and others have demonstrated a correlation between the mass of these holes and the total mass of stars in the galactic centers: the black hole mass is about 0.1 percent of the stellar mass. The same correlation applies to most (though not all) AGN galaxies. Some process, therefore, has linked central black holes to star formation. Lingering discrepancies show that researchers do not fully understand the link.

An AGN-starburst connection might even lurk a mere 24,000 light-years away—at the core of our own galaxy. Rapid motions of stars and gas around the galaxy's center betray the presence of a concentrated mass equal to that of 2.6 million suns. The radio and x-ray emission from this location indicates that the mass is a supermassive black hole—not a truly active hole but one that does feed occasionally. Some have hypothesized that it operates like a mini AGN, slurping up surrounding material at one ten-millionth the rate of a true AGN. Although it is not currently accompanied by a starburst, bright clusters

DON DIXON

FOUR WAYS TO RELATE BLACK HOLES AND STARBURSTS



of stars do reside nearby. They could be left over from a burst of star formation several million years ago.

Two other forms of evidence come from looking back in time. Observers have noticed that AGNs and star formation were even more closely related when the universe was a tenth of its current age. Back then, two types of galaxies were more common: ultraluminous infrared galaxies (called ULIRGs) and radio galaxies, which appear to be galaxies either in an early stage of formation or in the process of a galaxy merger. Their cores contain huge amounts—billions of solar masses—of cold, dense gas. And they host both AGNs and intense starbursts. The other historical approach concerns distant and luminous AGNs—specifically, quasars. They frequently live in messy galaxies, whose distorted shapes and unusual colors suggest that they are merging and forming stars at a high rate.

A final line of evidence derives from the x-ray background radiation, a lesser-known cousin of the cosmic microwave background radiation. Studies of the background have unveiled a population of AGNs hidden from optical telescopes. This obscuration has a natural explanation: the AGNs were accompanied by starbursts, which choked the galaxies with dust [see "The Cosmic Reality Check," by Günther Hasinger and Roberto Gilli; Scientific American, March 2002].

Chicken or Egg?

THE AGN-STARBURST CONNECTION could have come about in four broad ways: the starburst and AGN are one and the same; some third process caused both the AGN and the starburst; the AGN caused the starburst; or the starburst caused the AGN.

The first scenario is a limited version of the older idea that AGNs are just a type of starburst. Although that idea proved to be wrong for most AGNs, it might work for some of them. Weak AGNs could conceivably be produced by extreme stellar activity rather than a supermassive hole. The activity would occur in such a small region that telescopes might mistake it for a hole. The jury is still out on this possibility.

The second scenario is that the "connection" is merely coincidence. The same processes could set the stage for both starbursts and AGNs. For instance, a galaxy merger could shove gas toward the center of the newly formed entity, inducing a starburst and, by providing fuel for a hole, triggering an AGN. Interestingly, theory predicts that the time it takes for a black hole to grow to supermassive proportions (about 10 million years) is similar to the typical lifetime of a starburst, which is also similar to the time it takes for two galaxies to merge together.

Most researchers, however, have gravitated to the remaining two scenarios, in which AGNs and starbursts are causally

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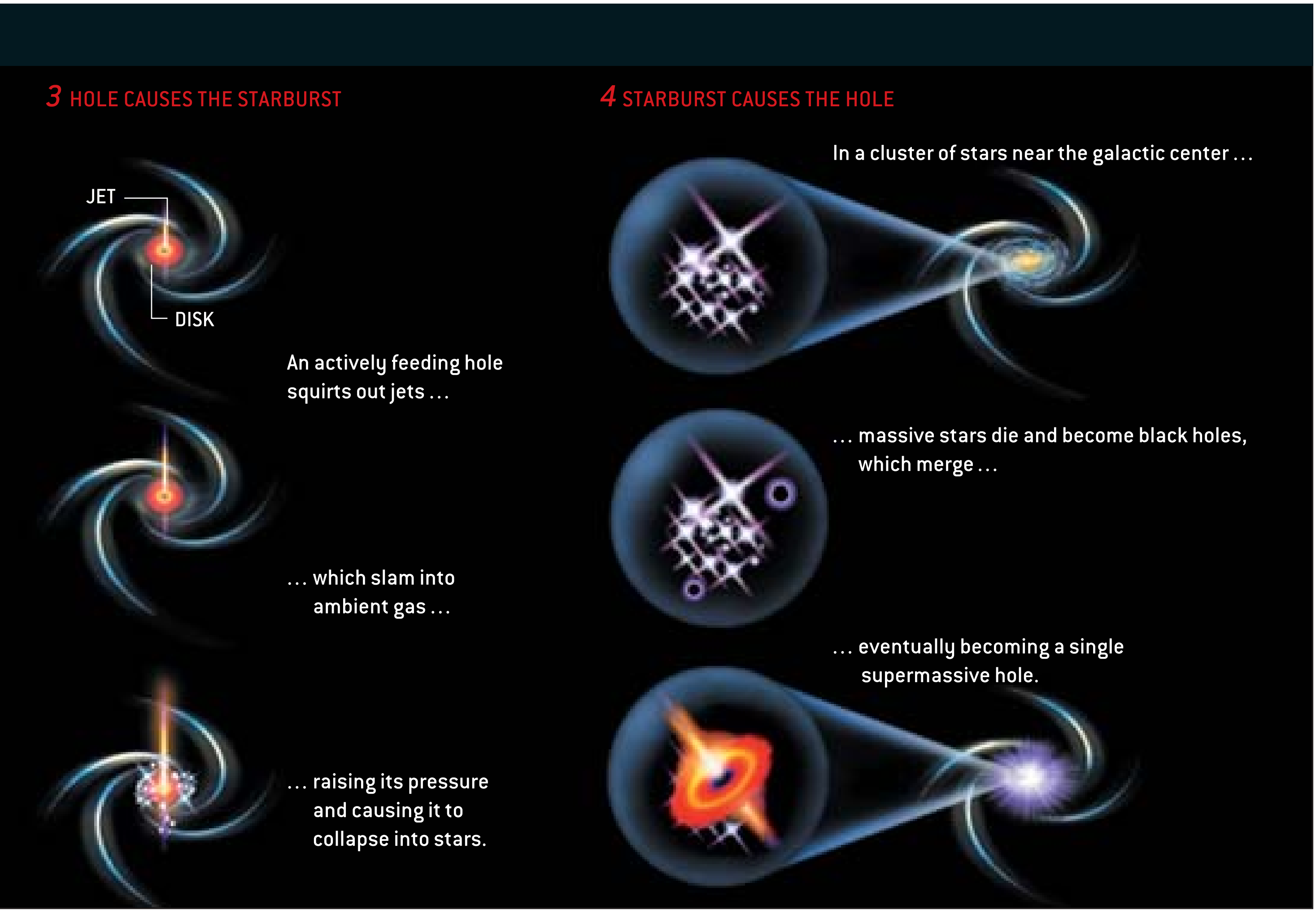

related. The third scenario posits that an existing supermassive black hole, contrary to expectation, exerts a strong influence on its host galaxy. Perhaps the hole pulls material toward the galactic center, enabling star formation. Françoise Combes of the Astronomical Observatory of Paris has championed this model. She argues that once a hole is in place, gas naturally flows into the galaxy core, fueling an AGN. As gas collects, it serves as the raw material for a starburst. The theory is quite plausible: many nearby galaxies that host AGNs also contain dusty structures within their cores, which could be material drawn in from outside. On the other hand, not all these structures have the theoretically predicted shape.

Instead of resulting from an inflow of material into the hole, a starburst might be set off by an outflow of energy from the hole. When the supermassive black hole starts to devour material and produce an AGN, shock waves and jets may rip through the galaxy. Gas piles up along shock fronts and condenses into stars. Chandra observations of the Centaurus A galaxy, where the star formation rate is extremely high, suggest that a massive AGN outburst occurred about 10 million years ago. In the outskirts of the galaxy lies a ring of x-ray emission about 25,000 light-years across, which may have resulted from the shock waves of this explosion. The explosion coincided with an episode of star formation, and the x-ray ring overlaps with arcs of young stars.

The black-hole-comes-first scenario has interesting implications. Black holes, rather than stars, may have been the first beacons in the utter blackness of the early universe. Moreover, some astronomers have suggested that the sun was born during a starburst. If this event was triggered by an AGN in the Milky Way, we may owe our existence to a black hole.

Digging a Hole

THE STARBURST-COMES-FIRST scenario, though, has the most theoretical and empirical support. The connection can result naturally from normal stellar evolution. A starburst creates dense clusters of stars, within which stellar collisions are common [see "When Stars Collide," by Michael Shara; SCIENTIFIC

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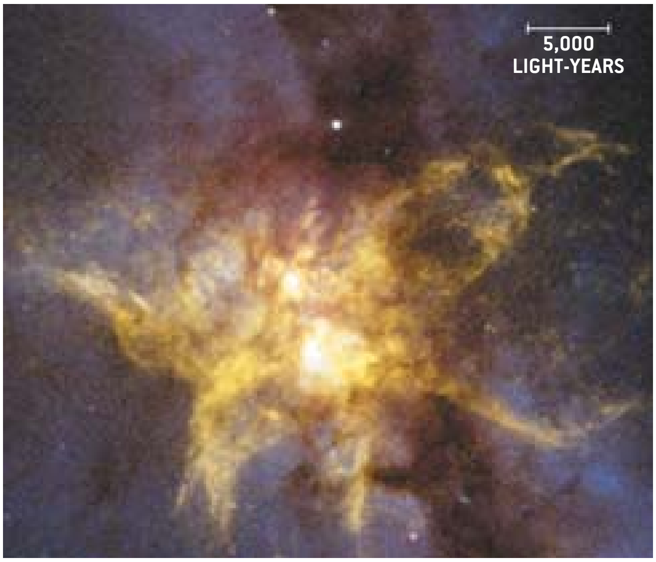
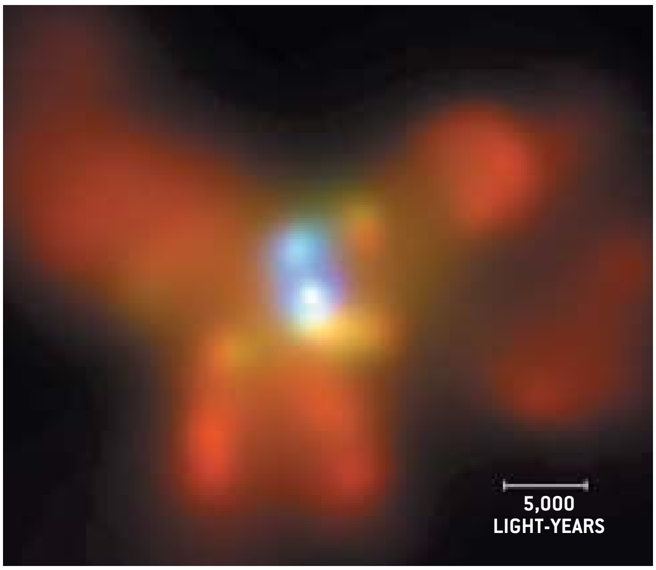




DOUBLE TROUBLE: As its strange butterfly shape suggests (*top*), NGC 6240 is not one galaxy but a pair of galaxies that recently merged. The system appears to have not one but two supermassive black holes, which show up as distinct sources of x-rays (*blue circles on bottom image*). Diffuse x-ray-emitting gas (*red*) is a sign of rapid star formation. NGC 6240 is a classic example of how holes, starbursts and galaxy mergers occur together.

AMERICAN, November 2002]. Massive stars in the cluster quickly die and become neutron stars or stellar-mass black holes, and these bodies agglomerate together. Over tens of millions to hundreds of millions of years, they build up a more massive black hole.

Alternatively, a large black hole could arise from lightweight stars similar to our sun, which do not normally turn into holes. In a dense cluster, these stars could undergo a runaway process of mergers, in which the stars collide and form massive stars, which then join further into megastars a few hundred to a few thousand times as heavy as our sun. Those megastars then collapse to form black holes of similar mass. This process would also take about 100 million years—much less than the lifetime of a galaxy and fast enough to account for the earliest quasars.

No matter how they are created, the black holes would tend to sink into the center of the galaxy. Several could merge to form a supermassive one. This idea has been bolstered by observations of the galaxy NGC 6240, in which a pair of supermassive black holes are circling each other, destined to merge [*see illustration at left*]. Supermassive black holes can continue to grow by feasting on surrounding material. Even star clusters that form in distant reaches of a galaxy can contribute mass to the central hole. Those clusters slowly lose kinetic energy and angular momentum because of friction on a galactic scale, caused by dynamical and gravitational interactions with the rest of the galaxy. They spiral inward and eventually get torn apart by tidal forces. Over the course of billions of years, this process could inject into the central black hole a mass equivalent to tens of millions of suns. Disturbances of the galaxy disk, such as an interaction or merger, could likewise pour fuel into the black hole.

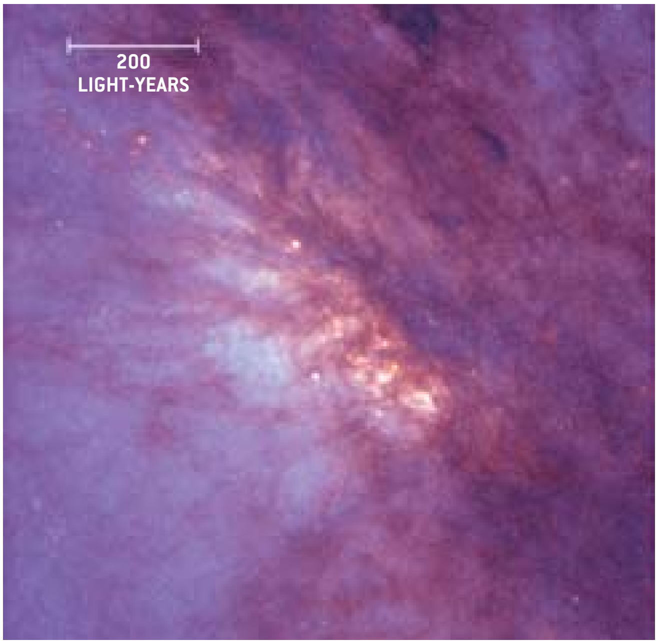
Middleweights

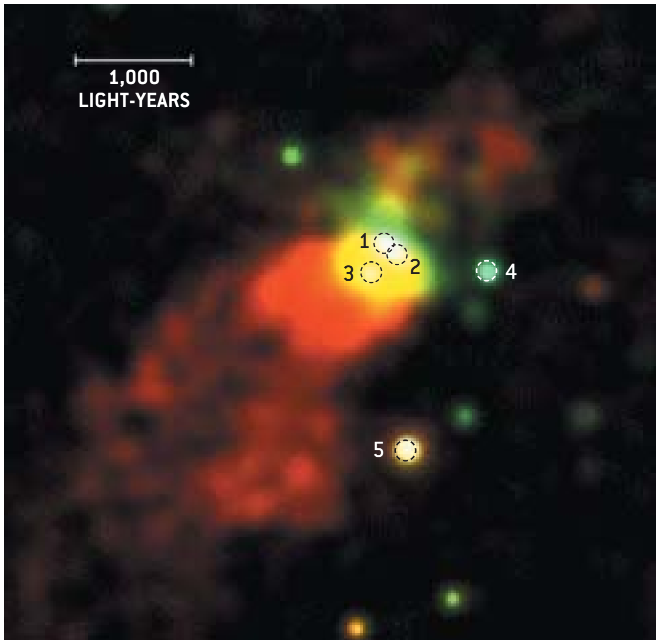
THE STARBURST-COMES-FIRST model predicts an entirely new population of black holes, intermediate between stellar-mass black holes and supermassive ones. Over the past 10 years, circumstantial evidence for these midsize holes has emerged in the form of so-called ultraluminous x-ray sources. Found in several nearby galaxies, these sources emit 10 times to several hundred times as much x-ray power as neutron stars or stellar-mass black holes [see "Hole in the Middle," by George Musser; News Scan, SCIENTIFIC AMERICAN, April 2001]. They might be neutron stars whose light is beamed in our direction, making them appear abnormally powerful. But evidence is accumulating that they are in fact black holes with a mass of up to several hundred times the mass of the sun.

Last year two teams of astronomers, led respectively by Roeland P. van der Marel of the Space Telescope Science Institute in Baltimore and Michael Rich of the University of California at Los Angeles, found hints of intermediate-mass holes at the centers of two dense star clusters, M15 and M31-G1. Stars in these clusters are moving so quickly that it would take bodies of 2,000 and 20,000 solar masses, respectively, to confine them. The "bodies" do not have to be large black holes—they could be a batch of neutron stars or small black holes. But even if that is the case, those objects should eventually merge and produce a large black hole.

Tod Strohmayer and Richard Mushotzky of the NASA Goddard Space Flight Center recently discovered that one of the ultraluminous sources, located near the center of the starburst galaxy M82, flickers with a period of about 18 seconds. The flickering is too slow and irregular to come from the surface of a neutron star and too intense to come from material in orbit around such a star. If it comes instead from material in orbit around a black hole, the hole could have a mass of several thousand suns. In the spiral galaxy NGC 1313, Jon Miller of the Harvard-Smithsonian Center for Astrophysics and his colleagues found two ultraluminous x-ray sources that are cooler than stellar-mass black holes. Theory predicts that the temperatures near black holes decrease as their mass increases, so the holes in NGC 1313 must be more massive than stellar-mass holes.

NASA/ROELAND P. VAN DER MAREL AND JORIS GERSSEN *Space Telescope Science Institute* (optical), NASA/CXC/STEFANIE KOMASSA *Max Planck Institute for Extraterrestrial Physics* (x-ray)





SMOKING GUN? The central region of galaxy NGC 253 (*left*) suggests that starbursts can build up supermassive black holes. Five x-ray sources (*circles on right image*) are brighter than stellar-mass black holes but dimmer than supermassive ones. They could be medium-size black holes, an intermediate step in the process of creating big holes from mergers of dead stars. Fuzz in the x-ray image is gas associated with star formation.

NASA/SAO/CXC (*x-ray*), EUROPEAN SOUTHERN OBSERVATORY (*optical*)

These candidate middleweight holes are not located at the centers of their host galaxies, so their relevance to the AGN-starburst connection is not firmly established. But my studies of one nearby starburst galaxy, NGC 253, have provided some direct clues. Before 1995, astronomers believed that the energetic x-rays from this galaxy originated in the hot gas associated with the starburst. In that year, I found hints of black holes in the x-ray spectrum. It was not until 2001, however, that my colleagues and I obtained an x-ray image of this galaxy with Chandra [*see illustration above*].

We found five ultraluminous x-ray sources within the inner 3,000 light-years of NGC 253. One of them, located exactly at the center of the galaxy, is about 100 times as bright as a neutron star or stellar-mass hole, suggesting that it has a mass equivalent to about 100 suns. It could be a black hole caught in the act of developing into a full-fledged AGN. The sequence of events might go as follows: A starburst takes place near the center of the galaxy. The massive stars thus formed collapse and merge to form lightweight black holes, which then spiral to the galactic center and merge, forming the seed for a supermassive hole. As the starburst winds down, the supermassive hole starts to power an AGN.

Studying how starburst activity affects the fueling and growth of a supermassive hole should offer insight into the birth of the most powerful of all AGNs, quasars. Astronomers have wondered why quasars in the early universe were much more powerful than present-day AGNs. The reason may be simply that the early universe had more frequent episodes of star formation, which triggered more intense AGNs.

To be sure, the situation may be more complicated than a straightforward triggering of one type of activity by the other. Galaxies could cycle between an AGN phase and a starburst phase. When the cycles overlapped, astronomers would see both phenomena together. AGNs and starbursts may even evolve in unison. Current observations are not able to tell whether the AGN comes first, the starburst comes first, or they both occur together. This fascinating question should be answered with the next generation of telescopes.

Observations with the Space Infrared Telescope Facility, which NASA plans to launch this year, will illuminate the AGN-starburst connection in the earliest galaxies. Scientists will be able to compare infrared, visible-light and x-ray data to determine whether AGNs or starbursts dominate activity during galaxy formation, which could determine which came first. It is also important to find more nearby galaxies like NGC 253.

The AGN-starburst connection is perhaps the ultimate intergenerational link in the universe. Black holes represent the coalesced embers of bygone stars; starbursts represent the birth of vibrant young stars. It may have taken a partnership of the old and the new to shape galaxies, including ours. SA

MORE TO EXPLORE

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