Colossal Galactic Explosions

Enormous outpourings of gas from the centers of nearby galaxies may ultimately help explain both star formation and the intergalactic medium

by SylvainVeilleux, Gerald Cecil and Jonathan Bland-Hawthorn

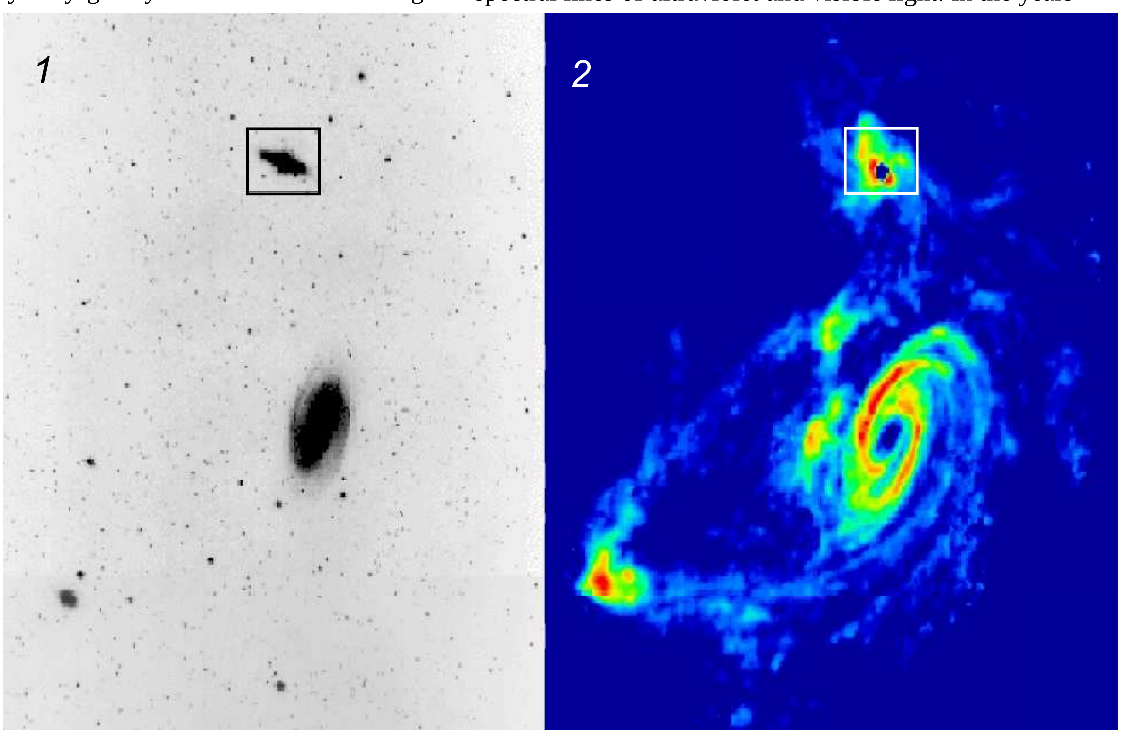
Millions of galaxies shine in the night sky, most made visible by the combined light of their billions of stars. In a few, however, a pointlike region in the central core dwarfs the brightness of the rest of the galaxy. The details of such galactic dynamos are too small to be resolved even with the Hubble Space Telescope. Fortunately, debris from these colossal explosions — in the form of hot gas glowing at temperatures well in excess of a million degrees — sometimes appears outside the compact core, on scales that can be seen directly from the earth.

The patterns that this superheated material trace through the interstellar gas and dust surrounding the site of the explosion provide important clues to the nature and history of the powerful forces at work inside the galactic nucleus. Astronomers can now determine what kind of engines drive these dynamos and the effects of their tremendous outpourings on the intergalactic medium.

Furthermore, because such cataclysms appear to have been taking place since early in the history of the universe, they have almost certainly affected the environment in which our own Milky Way galaxy evolved. Understanding how such events take place today may illuminate the distribution of chemical elements that has proved crucial to formation of stars like the sun.

Astronomers have proposed two distinctly different mechanisms for galactic dynamos. The first was the brainchild of Martin J. Rees of the University of Cambridge and Roger D. Blandford, now at Stanford University. During the early 1970s, the two sought to explain the prodigious luminosity — thousands of times that of the Milky Way — and the spectacular "radio jets" (highly focused streams of energetic material) that stretch over millions of light-years from the centers of some hyperactive young galaxies known as quasars. They suggested that an ultra-massive black hole — not much larger than the sun but with perhaps a million times its mass — could power a quasar.

A black hole itself produces essentially no light, but the disk of accreted matter spiraling in toward the hole heats up and radiates as its density increases. The inner, hotter part of the disk produces ultraviolet and x-ray photons over a broad range of energies, a small fraction of which are absorbed by the surrounding gas and reemitted as discrete spectral lines of ultraviolet and visible light. In the years



since Rees and Blanford proposed their model, astronomers have come to understand that similar black holes may be responsible for the energy output of nearer active galaxies.

As the disk heats up, gas in its vicinity reaches temperatures of millions of degrees and expands outward from the galactic nucleus at high speed. This flow, an enormous cousin to the solar wind that streams away from the sun or other stars, can sweep up other interstellar gases and expel them from the nucleus. The resulting luminous shock waves can span thousands of light-years —comparable to the visible sizes of the galaxies themselves — and can be studied from space or ground-based observatories. Some of these galaxies also produce radio jets: thin streams of rapidly moving gas that emit radio waves as they traverse a magnetic field that may be anchored within the accretion disk.

Black holes are not the only engines of galactic violence. Some galaxies apparently undergo short episodes of rapid star formation in their cores: so-called nuclear starbursts. The myriad new stars produce strong stellar winds and, as the stars age, a rash of supernovae. The fast-moving gas ejected from the supernovae strikes the background interstellar dust and gas and heats it to millions of degrees.

The pressure of this hot gas forms a cavity, like a steam bubble in boiling water. As the bubble expands, cooler gas and dust accumulate in a dense shell at the edge of the bubble, slowing its expansion. The transition from free flow inside the bubble to near stasis at its boundary gives rise to a zone of turbulence that is readily visible from the earth. If the energy injected into the cavity is large enough, the bubble bursts outinto the halo or beyond, thousands of light-years away from their origins.

Identifying the Engine

Both the starburst and the black-hole explanations appear plausible, but there are important differences between the two that may reveal which one is at work in a given galaxy. A black hole can convert as much as 10 percent of the infalling matter to energy. Starbursts, in contrast, rely on nuclear fusion, which can liberate only 0.1 percent of the reacting mass. As a result, they require at least 100 times as much matter, most of which accumulates as unburned fuel . Over the lifetime of a starburst-powered quasar, the total mass accumulated n the nucleus of the galaxy could reach 100 billion itimes the mass

M82 (box at top in 1,2) is 10 million light-years away, and is distinguished by an outpouring of incandescent gas from the area around its core (3). Astronomers have deduced that the upheaval is caused by the rapid formation of stars near the galactic nucleus. The resulting head and radiation cause the dust and gas from the galactic nucleus to rush into intergalactic space. The galaxy’s activity may have been triggered by the tidal interaction with its neighbor M81, which is invisible in the optical image (1) but striking in the radio image of atomic hydrogen (2).

of the sun, equivalent to the mass of all the stars in the Milky Way galaxy. The more mass near the nucleus, the more rapidly orbiting stars must move. Ground-based studies with visible-band light, which are limited by atmospheric blurring, have not placed tight constraints on the concentration of mass in galactic centers. However, in 1995, radio-telescopes revealed an accretion disk with an inner radius of half a light-year spinning rapidly around a mass 20 million times that of the sun at the center of nearby galaxy NGC 4258.

Several research groups have mapped the patterns of stellar motions across galactic nuclei using an efficient spectrograph installed on the Hubble telescope by astronauts in 1997. The early discovery that gas in the inner core of galaxy M87 is moving in a manner consistent with a black-hole accretion disk demonstrated the promise of such techniques, and subsequent studies have pointed to the presence of black holes at the center of most massive galaxies.

Starbursts and black holes also differ in the spectra of the most energetic photons they produce. Near a black hole, the combination of a strong magnetic field and a dense accretion disk creates a soup of very fast particles that collide with one another and with photons to generate x-rays and gamma rays. A starburst, in contrast, produces most of its high-energy radiation from collisions between supernova ejecta and the surrounding galactic gas and dust. This impact heats gas to no more than about a billion degrees and so cannot produce any radiation more energetic than X-rays. The large numbers of gamma rays detected from some quasars by the Compton Gamma Ray Observatory imply that black holes are at their centers [see "The Compton Gamma Ray Observatory," by Neil Gehrels, Carl E. Fichtel, Gerald J. Fishman, James D. Kurfess and Volker Schönfelder; SCIENTIFIC AMERICAN, December 1993].

A final difference between black holes and starbursts lies in the forces that focus the outrush of gas. The magnetic field-lines attached to the accretion disk around a black hole direct outflowing matter along the rotation axis of the disk in a thin jet. The material expelled by a star-burst bubble, in contrast, simply follows the path of least resistance in the surrounding environment. A powerful starburst in a spiral galaxy will spew gas perpendicular to the plane of the galaxy's disk of stars and gas, but the flow will be distributed inside an hour-glass-shaped region with a wide opening. The narrow radio jets that extend millions of light-years from the core of some active gal axes clearly suggest the presence of black holes.

All that we know about galaxies — active or otherwise — comes from the radiation they emit. Our observations supply the data that astrophysicists can use to choose among competing theories. The three of us have concentrated on visible light, from which we can determine the temperatures, pressures and concentrations of different atoms in the gas agitated by galactic explosions. We compare the wavelength and relative intensities of emission lines from excited or ionized atoms with those measured in terrestrial laboratories or derived from theoretical calculations.

Thanks to the Doppler shift, which changes the frequency and wavelength of light emitted by moving sources, this analysis also reveals how fast the gas is moving. Approaching gas emits light shifted toward the blue end of the spectrum, and receding gas emits light shifted toward the red end.

Until recently, astronomers unraveled gas behavior by means of two complementary methods: emission-line imaging and long-slit spectroscopy. The first produces images through a filter that selects light of a particular wavelength emitted by an element such as hydrogen. Such images often dramatically reveal the filamentary patterns of explosions, but they cannot tell observers anything about the speed or direction of the gases' motions, because the filter does not discriminate finely enough to measure redshifts or blueshifts. Long-slit spectrometers, which disperse light into its constituent colors, provide detailed information about gas motions but only over a tiny region.

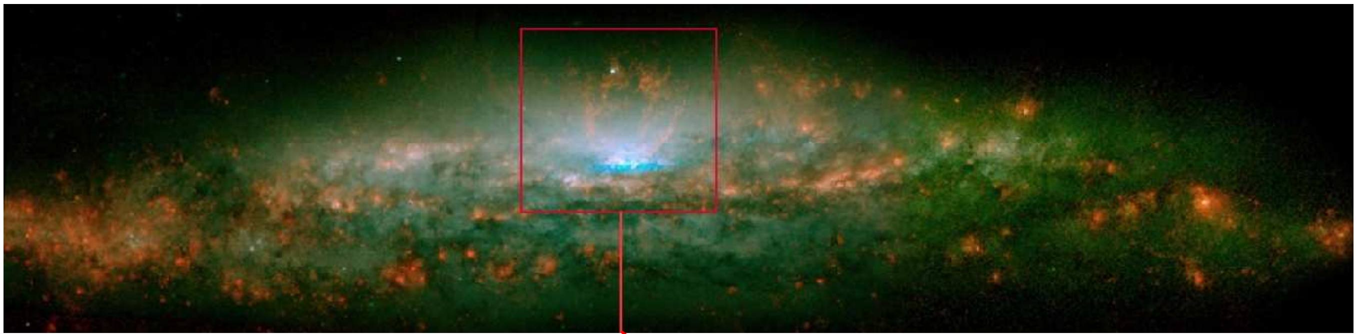
For a decade, our group used an instrument that combines the advantages of these two methods without the main drawbacks. The Hawaii Imaging Fabry-Perot Interferometer (HIFI) yields detailed spectral information over a large field of view. Named after the turn-of-the-century French inventors Charles Fabry and Alfred Perot, such interferometers have found wide-ranging applications in astronomy. At their heart are two glass plates that are kept perfectly parallel while separated by less than a twentieth of a millimeter. The inner surfaces of the plates are highly reflecting, so light passing through the plates is trapped into repeated reflections. Light of all but a specific wavelength — determined by the precise separation — is attenuated by destructive interference as the light waves bounce back and forth between the plates. By adjusting the separation between the plates, we can produce a series of images that are essentially a grid of spectra obtained by the interferometer at every position over the field of view.

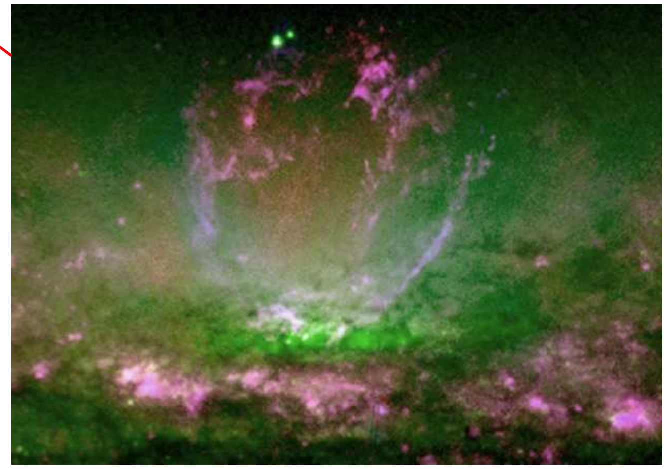
The HIFI takes its pictures atop the 14,000-foot dormant volcano Mauna Kea, using the 2.2-meter telescope owned by the University of Hawaii and the 3.6-meter Canada-France-Hawaii instrument. The smooth airflow at the mountaintop produces sharp images. Charge-coupled devices, which are very stable and sensitive to faint light, collect the photons. In a single night, this powerful combination can generate records of up to a million spectra across the full extent of a galaxy.

Nearby Active Galaxies

We have used the HIFI to explore NGC 1068, an active spiral galaxy 46 million light-years away. As the nearest and brightest galaxy of this type visible from the Northern Hemisphere, it has been studied extensively. At radio wavelengths, NGC 1068 looks like a miniature quasar: two jets extend about 900 light-years from the core, with more diffuse emission from regions farther out. Most likely, emission from gaseous plasma moving at relativistic speeds creates the radio jets, and the "radio lobes" arise where the plasma encounters matter from the galactic disk. As might a supersonic aircraft, the leading edge of the northeast jet produces a V-shaped shock front.

The same regions also emit large amounts of visible and ultraviolet light. We have found, however, that only 10 percent of the light comes from the nucleus. Another 5 percent comes from galaxy-disk gas that has piled up on the expanding edge of the northeast radio lobe. All the rest comes from two fans of high-velocity gas moving outward from the center at speeds of up to 1,500 kilometers per second.





STARBURST, a sudden pulse of star formation, may be responsible for the burst of activity of NGC 3079, even though the galaxy has a black hole at its center. We made these images with the Hubble Space Telescope. A close-up view of the area near the nucleus outlines an enormous bubble, 3500 light-years across, that has been blown into the interstellar medium by hot stars forming at the galaxy's center.

The gas flows outward in two conical regions; it is probably composed of dense filaments of matter that have been swept up by the hot wind from the accretion disk. The axis of the cones of outflowing wind is tilted above the plane of the galaxy but does not point toward the poles.

The effects of the activity within the nucleus reach out several thousand light-years, well beyond the radio lobes. The diffuse interstellar gas exhibits unusually high temperatures and a large fraction of the atoms have lost one or more electrons and become ionized. At the same time, phenomena in the disk appear to influence the nucleus. Infrared images reveal an elongated bar of stars that extends more than 3,000 light-years from the nucleus. The HIFI velocity measurements suggest that the bar distorts the circular orbits of gas in the disk, funneling material toward the center of the galaxy. This inflow of material may fuel the black hole.

Another tremendous explosion is occurring in the core of one of our nearest neighbor galaxies, M82, just a few million light-years away. In contrast to NGC 1068, this cataclysm appears to be an archetypal starburst-driven event. Images exposed through a filter that passes the red light of forming hydrogen atoms reveal a web of filaments spraying outward along the galactic poles. Our spectral grids of emission from filaments perpendicular to the galactic disk reveal two main masses of gas, one receding and the other approaching. The difference in velocity between the two increases as the gas moves outward from the core, reaching about 350 kilometers per second at a distance of 3,000 light-years. At a distance of 4,500 light-years from the core, the velocity separation diminishes.

The core of M82 is undergoing an intense burst of star formation, possibly triggered by a recent orbital encounter with its neighbors M81 and NGC 3077. Its infrared luminosity is 30 billion times the total luminosity of the sun, and radio astronomers have identified the remnants of large numbers of supernovae. The filamentary web visible from the earth results from two elongated bubbles oriented roughly perpendicular to the disk of M82 and straddling the nucleus. X-ray observatories in space have detected the hot wind that inflates these bubbles; their foamy appearance probably arises from instabilities in the hot gas as it cools.

Ambiguous Activity

Unfortunately, the identity of the principal source of energy in active galaxies is not always so obvious. Sometimes a starburst appears to coexist with a black-hole engine. Like M82, many of these galaxies are abnormally bright at infrared wavelengths and rich in molecular gas, the raw material of stars. Radio emission and visual spectra resembling those of a quasar, however, suggest that a black hole may also be present. Such ambiguity plagues interpretations of the behavior of the nearby galaxy NGC 3079. This spiral galaxy appears almost edge-on from the earth — an excellent vantage point from which to study the gas expelled from the nucleus. Like M82, NGC 3079 is anomalously bright in the infrared, and it also contains a massive disk of molecular gas spanning 8,000 light-years around its core. At the same time, the core is unusually bright at radio wavelengths, and the linear shape of radio-emitting regions near the core suggests a collimated jet outflow. On a larger scale, the radio-emission pattern is complex and extends more than 6,500 light-years from either side of the galactic disk.

Images made in red hydrogen light show a nearly circular ring 3,600 light-years across just east of the nucleus; Velocity measurements from the HIFI confirm that the ring marks the edge of a bubble as seen from the side. The bubble resembles an egg with its pointed extremity balanced on the nucleus and its long axis aligned with the galactic pole. There is another bubble on the west side of the nucleus, but most of it is hidden behind the dusty galaxy disk.

Our spectral observations imply that the total energy of this violent outflow is probably comparable to that of the explosions in NGC 1068 or M82. The aligment of the bubble along the polar axis of the host galaxy implies that galactic dust and gas, rather than a central black hole, are collimating the outflow. Nevertheless, the evidence is clear that NGC 3079 contains a massive black hole at its core.

Is the nuclear starburst solely responsible for such a gigantic explosion? We have tried to answer this question by analyzing the infrared radiation coming from the starburst area. Most of the radiation from young stars embedded in molecular clouds is absorbed and reemitted in the infrared, so the infrared luminosity of NGC 3079's nucleus may be a good indicator of the rate at which supernovae and stellar winds are injecting energy at the center of the galaxy.

When we compare the predictions of the starburst model with our observations, we find that the stellar ejecta appear to have enough energy to inflate the bubble. Although the black hole presumed to exist in the core of NGC 3079 may contribute to the outflow, there is no need to invoke it as an energy source.

How Active Galaxies Form

Although astronomers now understand the basic principles of operation of the engines that drive active galaxies, many details remain unclear. There is a vigorous debate about the nature of processes that ignite a starburst or form a central black hole. What is the conveyor belt that transports fuel down to the pointlike nucleus? Most likely, gravitational interactions with gas-rich galaxies redistribute gas in the host galaxy, perhaps by forming a stellar bar such as the one in NGC 1068. Computer simulations indicate that the bar, once formed, may be stable [see "Colliding Galaxies," by Joshua Barnes, Lars Hernquist and François Schweizer; SCIENTIFIC AMERICAN, August 1991]. (Indeed, the bar must be stable, because NGC 1068 currently has no close companion.)

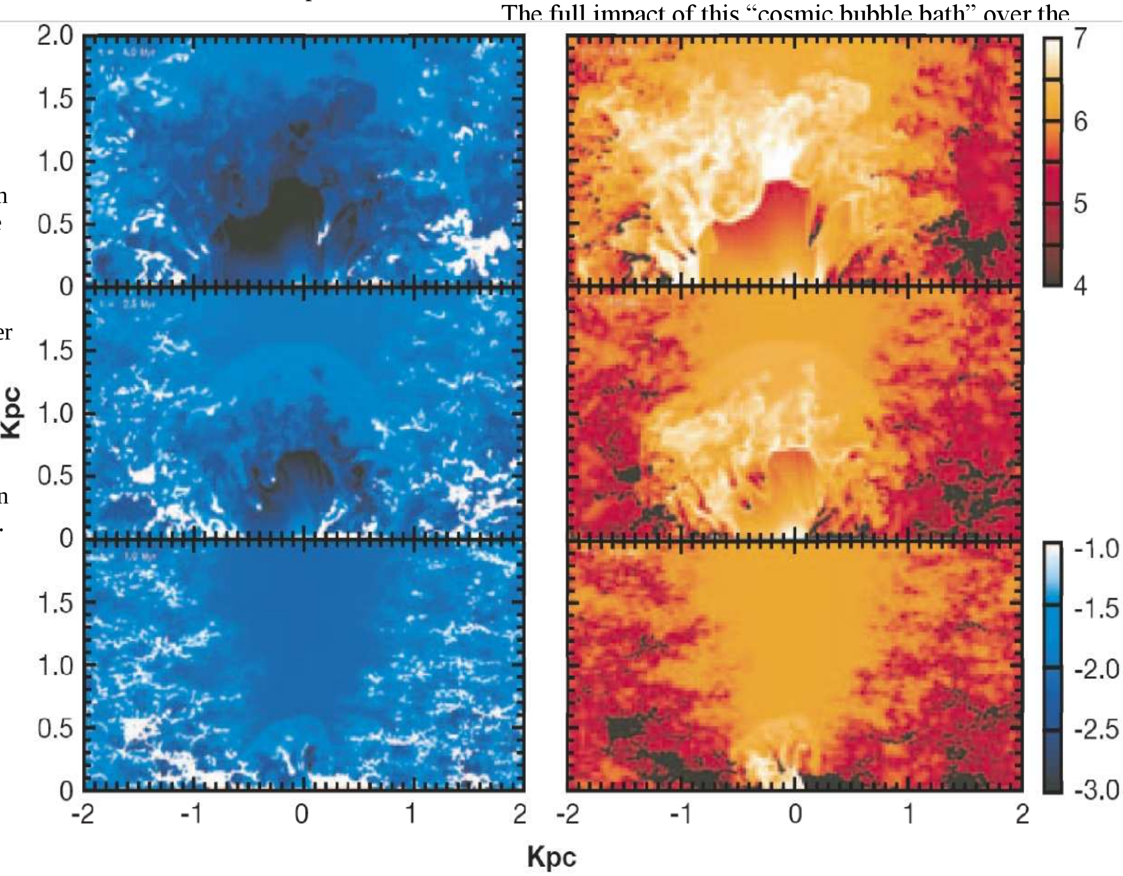
Researchers are also divided on which comes first, nuclear starburst or black-hole. Perhaps the starburst is an early phase in the evolution of active galaxies, eventually fading to leave a dense cluster of stellar remnants that rapidly coalesce into a massive black hole.

The anomalous gas flows in the galaxies that we and others have studied are almost certainly only particularly prominent examples of widespread, but more subtle, processes that affect many more galaxies. Luminous infrared galaxies are common, and growing evidence is leading astronomers to believe that many of their cores are also the seats of explosions. These events may profoundly affect the formation of stars throughout the galactic neighborhood.

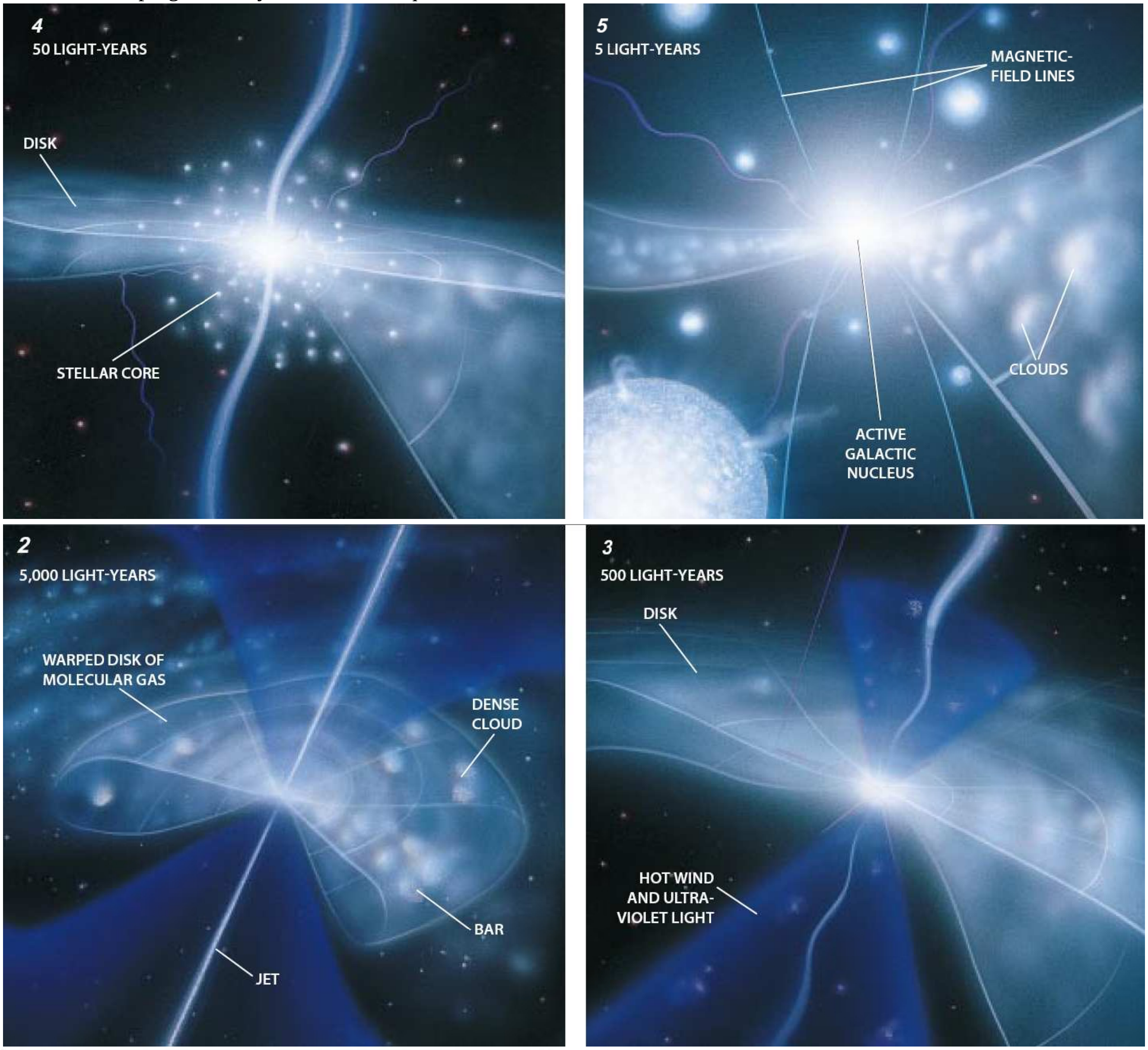
The bubble in NGC 3079, for instance, is partially ruptured at the top and so probably leaks gas into the outer galactic halo or even into the vast space between galaxies. Nuclear reactions in the torrent of supernovae unleashed by the starburst enrich this hot wind in heavy chemical elements. As a result, the wind will not only heat its surroundings but also alter the environment's chemical composition.

The full impact of this "cosmic bubble bath" over the

OUTPOURING OF GAS rapidly becomes turbulent in this computer simulation of a starburst-driven active galaxy. Temperature maps (right) show how the hot gas emanating from the nucleus displaces the cooler galactic gas around it. The resulting shock fronts appear clearly in maps of gas density (left). Time increases from bottom to top. Distances are shown in three thousand light-years.



history of the universe is difficult to assess accurately because we currently know very little of the state of more distant galaxies. Images of such galaxies taken by the Hubble are helping to clarify some of these questions. Indeed, as the light that left those galaxies billions of years ago reaches our instruments, we may be watching an equivalent of our own galactic prehistory unfolding elsewhere in the universe.



COLOSSAL FORCES at work in the center of an active galaxy can make themselves felt more than a million light-years away as jets of gas flow into the intergalactic medium to create enormous shock waves (1). Closer to the center of the galaxy (2,3), a dense equatorial disk of dust and molecular gas feeds matter to the active nucleus while hot gas and radiation spill out along the poles. The high density of the infalling gas within a few dozen light-years of the center causes a burst of star formation (4). Even closer to the center (5), the disk, glowing at ultraviolet and x-ray wavelengths, tapers inward to feed what astronomers believe is a black hole containing many millions of stellar masses but still so small as to be invisible on this scale.