The Most Distant Radio Galaxies

Astronomers have identified powerful radio-emitting galaxies that existed when the universe was only one tenth its present age. These objects offer a glimpse at the early evolution of giant galaxies

by George K. Miley and Kenneth C. Chambers

In 1946 a group of researchers at the Royal Radar Establishment in Malvern, England, discovered that intense radio emissions were emanating from a tiny region of the constellation Cygnus. Seven years later Walter Baade and Rudolph Minkowski of Hale Observatories trained the giant, 200-inch Mount Palomar telescope on the site of that radio source and found a peculiar double object they speculated might be two galaxies in collision. Subsequent work established that the source, known as Cygnus A, lies at a surprisingly great distance, 650 million light-years from the earth. That Cygnus A could be detectable at such a distance led Baade and Minkowski to conclude that it is a source of extraordinary power.

Since then, astronomers have found that Cygnus A is just one member of an entire class of active galaxies that radiate with as much as a million times the luminosity of the Milky Way. The relations between the disparate kinds of active galaxies and the nature of the mechanism that enables them to radiate so intensely have remained enduringly mysterious. Over the past two decades, however, observers and theorists have increasingly become convinced that loud radio emission is but one manifestation of the energetic processes taking place near an extremely massive collapsed object—a black hole having perhaps a billion times the mass of the sun.

By homing in on radio signals from such objects, we and several colleagues have located the most distant galaxies known. These objects are so remote that it has taken their radiation billions of years to reach the earth. Astronomers are seeing them as they were when the universe was only one tenth its present age of about 15 billion years. The most youthful active galaxies differ in several noteworthy ways from their older, more proximate relatives, and hence they offer clues about how massive galaxies form and evolve. These findings are even providing insight into the origin of the universe.

The diversity of radio-emitting galaxies became apparent as researchers sought out the visible counterparts to the radio sources listed in the 3C (third Cambridge) catalogue compiled in the late 1950s by Martin Ryle and his group at the University of Cambridge. Roughly 70 percent of the sources in the catalogue, including Cygnus A, are classified simply as radio galaxies. Most of the relatively nearby examples of these objects look more or less like normal giant elliptical galaxies. During the past few years, astronomers have observed extraordinarily distant radio galaxies; these objects have peculiar, irregular structures.

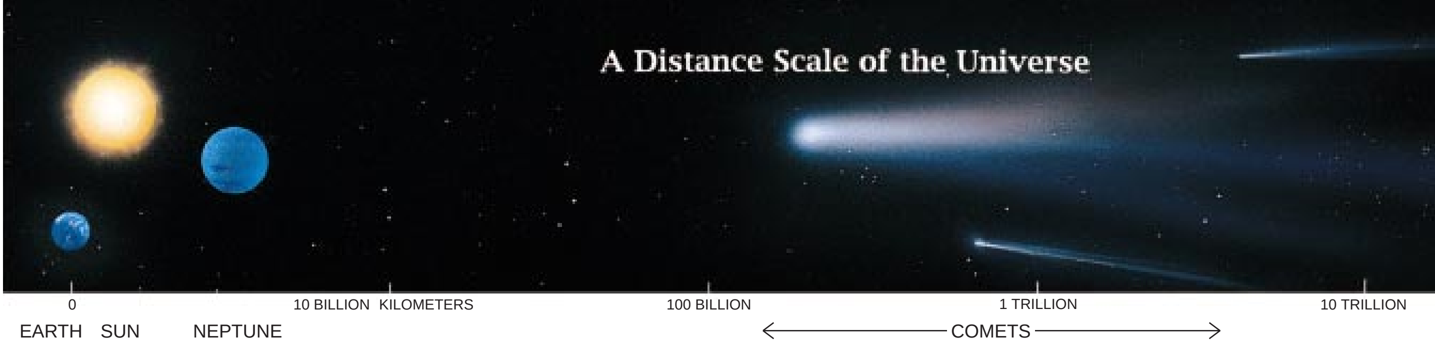
Scientists now know that radio galaxies are just one of a bewildering assortment of active galaxies that radiate with astounding power. The other main class of active galaxy consists of the quasistellar radio sources, or quasars, so named because of their starlike appearance. Unlike radio galaxies, quasars in no way resemble normal galaxies; furthermore, contrary to their name, 90 percent of quasars are quiet at radio wavelengths.

In 1963 Maarten Schmidt of the California Institute of Technology deduced from the spectra of the brightest quasars that they lie far beyond the stars of the Milky Way. Researchers have since established that quasars are the brilliant, tiny central regions of distant galaxies whose outer parts are difficult to detect because of the intense glare. The starlike appearance of quasars belies the fact that they are among the most luminous objects in the universe.

Some active galaxies display less extreme forms of activity. For example, Seyfert galaxies have bright centers that resemble tame quasars, but the body of the spiral galaxy surrounding the center is clearly evident. Indeed, astronomers are coming to recognize that the line between active galaxies and ostensibly normal ones is far blurrier than once believed. The central regions of many—perhaps most—massive galaxies

GEORGE K. MILEY and KENNETH C. CHAMBERS have spent the past seven years hunting for the most distant galaxies on the basis of their distinctive radio emissions. Miley is a professor of astronomy at Leiden University in the Netherlands. He obtained a Ph.D. in radio astronomy from the University of Manchester in 1968. During the 1970s, he used the large radio telescope at Westerbork, the Netherlands, to study steep-spectrum radio sources, laying the groundwork for the technique described in this article. From 1984 to 1988 Miley was at the Space Telescope Science Institute in Baltimore, where he headed the academic affairs branch; while there he initiated a search for distant radio galaxies, which became Chambers's Ph.D. thesis project. Chambers is now a professor of astronomy at the Institute for Astrophysics of the University of Hawaii at Honolulu.

MOST DISTANT KNOWN GALAXY, which is called 4C 41.17, may lie more than 12 billion light-years from the earth. This false-color image was taken by the *Hubble Space Telescope*. The galaxy's irregular shape looks startlingly unlike the smooth, elliptical form of most relatively nearby radio-emitting galaxies. The contour lines map out the intense radio emanations from 4C 41.17. Astronomers are debating why the shape of the radio source around the more distant of these so-called radio galaxies roughly aligns with their visible appearance.



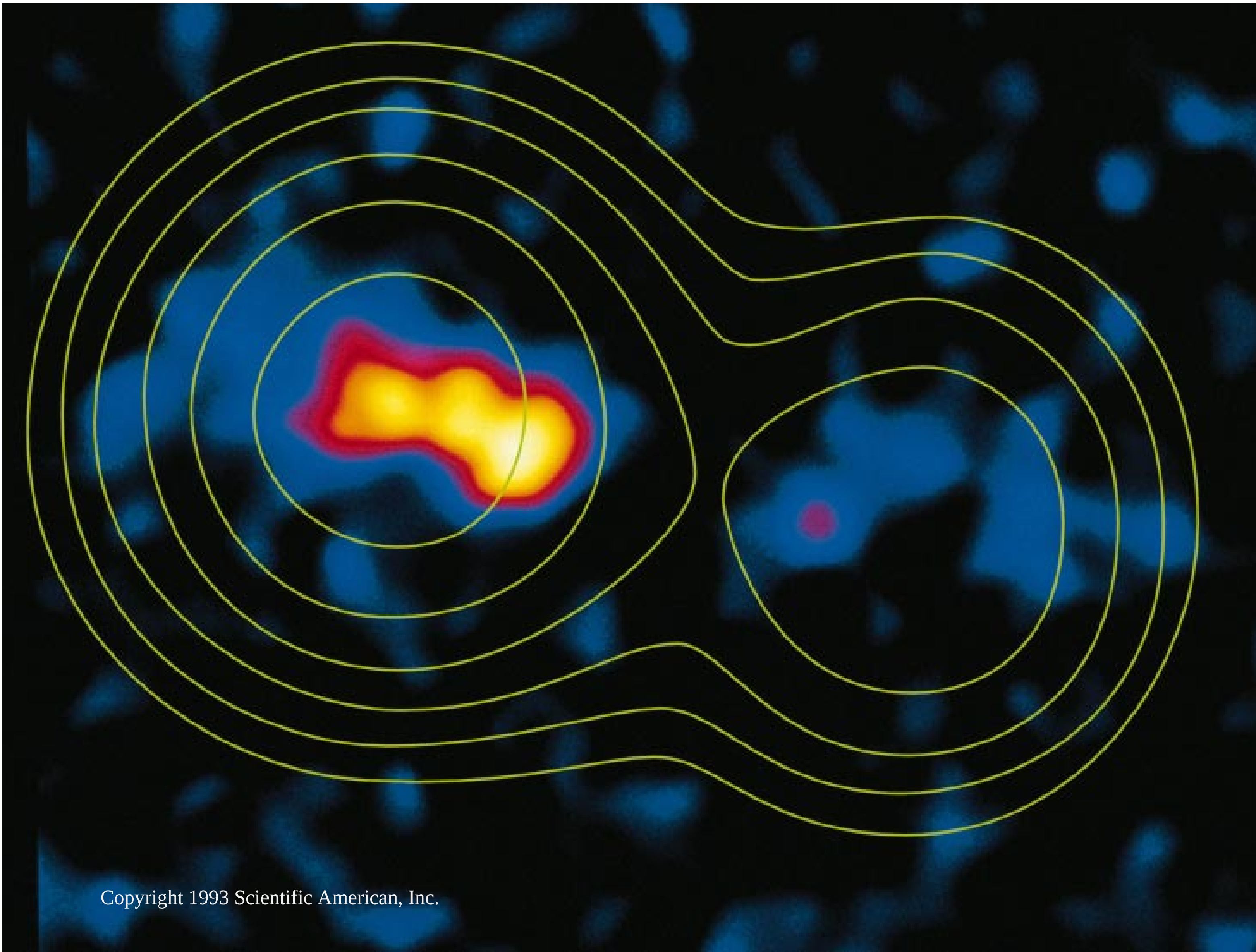
contain radio sources and some heightened concentration of light.

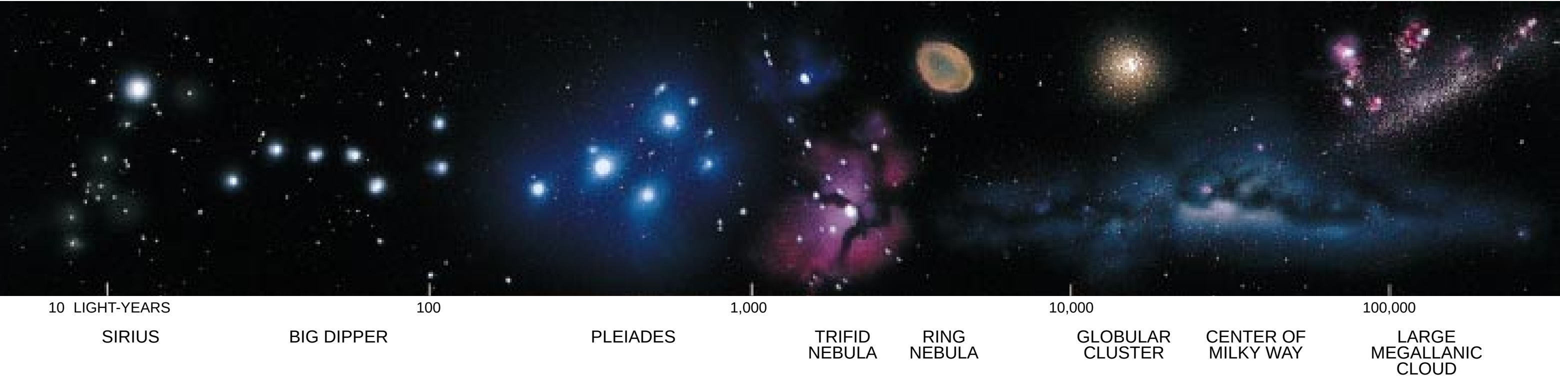
Using a newly developed technique known as radio interferometry, astronomers showed that many kinds of active galaxies share a common radio structure. Interferometry is accomplished by linking together two or more telescopes to create, in essence, a single, much more precise instrument. When so arranged, radio telescopes can provide much sharper images than those from even the largest optical telescopes.

Studies made during the past three decades using interferometry revealed that radio galaxies and quasars usually display two symmetric, radio-emitting lobes that straddle and dwarf their optical parent galaxies. The largest sources stretch more than 10 million light-years across, or more than 20 times the visible extent of the typical host galaxy and more than 100 times the diameter of the Milky Way. The nature of the radio emission implies that it is produced by electrons traveling at velocities approaching the speed of light as they pass through a magnetic field.

In 1971 Martin J. Rees of Cambridge suggested that hidden engines located within the nuclei of the parent galaxies generate the energy needed to power the giant radio lobes. Rees and Roger D. Blandford, now at Caltech, proposed that high-speed particles shooting along narrow channels could transport the energy. A few years later other investigators demonstrated that in many sources jetlike features do indeed seem to connect a radio-bright core in the galaxy's nucleus with knots of radio emission emanating from the outer extremities of the lobes. The jets are thought to mark the path of the subatomic particles racing from the nucleus.

The nature of the engine that powers the violent processes in radio galaxies and quasars is still a mystery, but most astronomers think a massive rotating black hole lies behind all the commotion. Einstein's theory of relativity pre-





dicts the existence of objects whose gravity is so strong that nothing, not even light, can escape from within them; observers are actively seeking unequivocal evidence of such objects.

Theorists commonly suppose that material spiraling toward a black hole becomes compressed and heated to a temperature of millions of degrees before it vanishes into the hole's interior. The superheated particles circling the hole are thought to be responsible for the various exotic phenomena that occur in and around the centers of active galaxies, such as the formation of radio jets. The jets are thought to consist of collimated beams of particles that are spewed out along the black hole's rotation axis, perhaps by a kind of electromagnetic dynamo process.

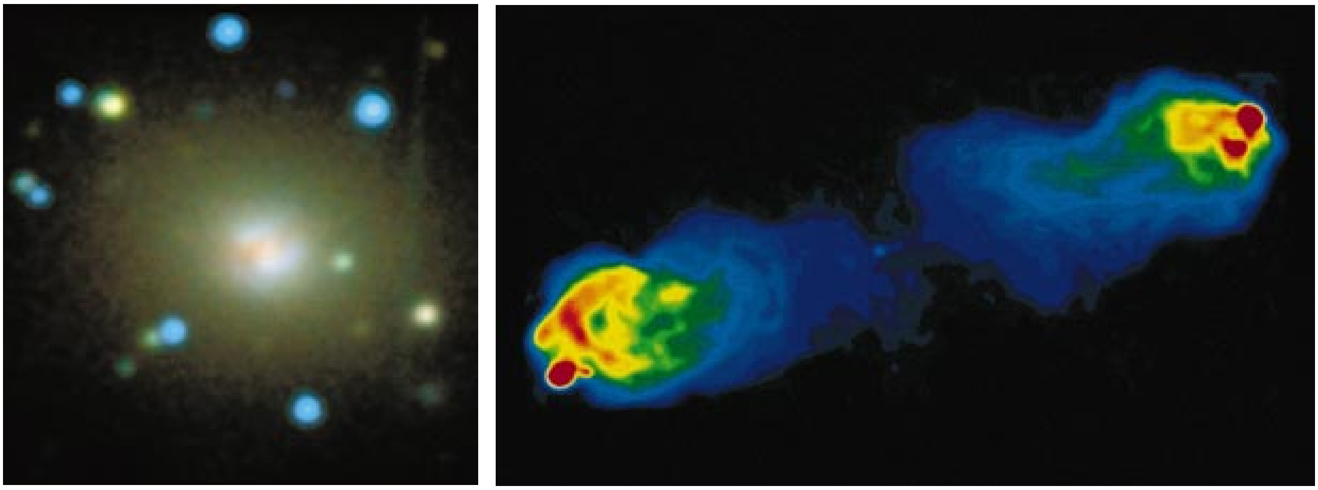
As a result of the advances in theory and observation, astronomers have begun to piece together a satisfying picture that unifies the different kinds of active galaxies. According to present thinking, one of the most significant factors determining the appearance of an active galaxy is the orientation of the radio jet—in particular, whether or not the jet is aimed toward the earth.

Several observations made during the past few years suggest that dust in the central region of an active galaxy can block all radiation except that emitted along the axis of the radio jet. Peter D. Barthel, while at Caltech, therefore proposed that all radio-emitting galaxies contain bright, embedded nuclei. If the radio source points earthward, the nucleus is visible, and the object is classified as a quasar. If the radio source is aligned in any other direction, the nucleus is more likely to be hidden from us, in which case the object is considered to be a radio galaxy.

Another likely influence on the observed properties of radio-emitting galaxies is the nature of the local environment surrounding the radio source. If the jets encounter regions of dense dust and gas, they will be unable to propagate outward, and the galaxy will not develop powerful radio-emitting lobes. Such environmental factors may explain why the most luminous radio sources form around giant elliptical galaxies, not around gas-rich spiral galaxies like the Milky Way.

The passage of time also must affect the behavior of an active galaxy. Variations in the degree of activity or the orientation of the central black hole would alter the luminosity and appearance of the radio source. Radio and optical emissions from the inner regions of active galaxies are known to fluctuate in intensity from year to year, so it is clear that conditions near the hole can change quite rapidly. Over millions of years, the black hole would gradually increase in mass and might deplete the nearby region of all material, snuffing out the activity.

As the number of known active galaxies has increased, astronomers have come to appreciate just how drastically the population of these objects has changed over the history of the universe. At great distances, where the universe is being seen as it was billions of years ago, quasars are far more abundant than they are nearby. Current surveys indicate that two billion years after the big bang, the density of bright quasars and other active galaxies in the universe was several hundred times greater than it is today [*see illustration on page 61*]. Many researchers have speculated that the era during which quasars were most common is somehow related to the formation of galaxies, but no direct link has yet been established. By examining the youngest, most distant radio galaxies, we and our colleagues hope to in-



CYGNUS A, one of the closest bright radio galaxies, is about 650 million light-years away. A new composite optical image made at several wavelengths (*left*) reveals a previously unseen darkish lane near the center of the galaxy, possibly the leftovers from a recent merger with a smaller galaxy. The huge filamentary, radio-emitting lobes (*right*) measure about 400,000 light-years across, several times the diameter of the visible part of the galaxy. The lobes are believed to be powered by twin jets of fast-moving particles ejected along the rotation axis of a black hole at the center of Cygnus A.

vestigate that relation and to uncover clues about the very early history of the universe.

Before we can discuss events that happened long ago in galaxies faraway, we must first introduce a few fundamental cosmological concepts. Measurements of distance in the universe depend on the fact that every atomic element emits and absorbs light at certain characteristic colors, or wavelengths, which show up as bright or dark lines in the spectra. In 1929 Edwin P. Hubble reported that the spectral lines associated with hydrogen, calcium and other elements show up redder (at longer wavelengths) in most galaxies than they do in the laboratory. This so-called redshift is caused by the overall expansion of the universe, which reddens, or stretches, the light. The farther away one looks, the greater the amount of expansion that has occurred and hence the greater the redshift.

The fractional shift in wavelength is usually denoted as *z*. Astronomers can measure the redshift of even a faint galaxy to within a fraction of a percent. If they knew the precise rate of the cosmic expansion and the true geometry of the universe, they could determine to a similar precision the distance to the galaxy and thereby infer its size and the amount of time that has passed since the light left that galaxy.

At present, however, the size and age of the universe are uncertain by a factor of two. Astronomers therefore find it more convenient to discuss how faraway an object is in terms of its redshift rather than its distance in light-years. Assuming that the universe is 15 billion years old and that its density matches that of the most popular cosmological models, a galaxy having a redshift of two is seen as it was 80 percent of the way back to the beginning of the universe, meaning it lies roughly 12 billion light-years from the earth; a galaxy at a redshift of four is seen as it was 90 percent of the way back.

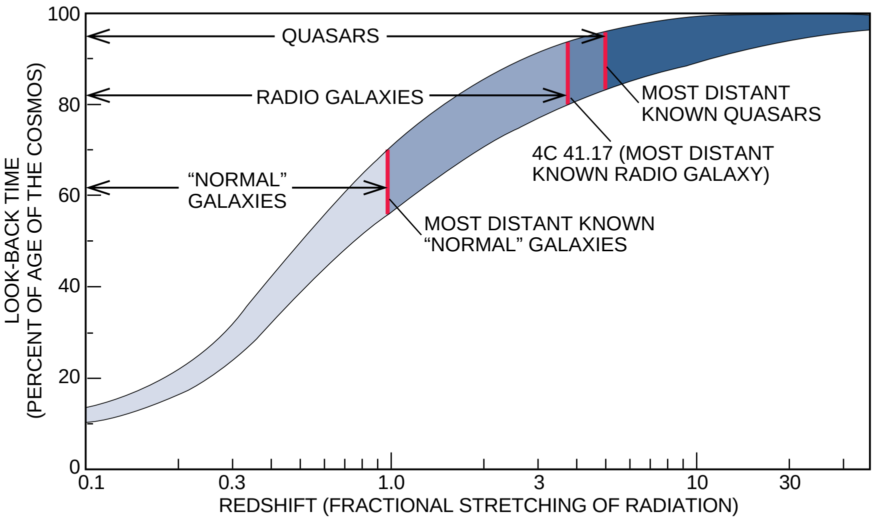
Studies of such distant radio galaxies provide a way to learn about events that occurred during the very first moments after the birth of the universe. Most cosmologists believe galaxies grew around small density fluctuations that arose less than 10^{-32} of a second after the big bang. According to current theory, most of the mass of the universe exists in the form of exotic particles known as cold dark matter. These particles interact with normal matter only through gravity, so they were able to collapse into clumps soon after the big bang, when normal matter was still too hot to do so. As the universe cooled, normal matter fell into the clumps of dark matter and ultimately formed galaxies.

In the simplest version of the cold dark matter model, galaxies would have coalesced so slowly that few of them could have formed at redshifts higher than two or three—that is, within the first couple of billion years after the big bang. Therefore, studies of galaxies dating from that time or earlier are crucially important in learning which cosmological models are promising and which ones need to be discarded.

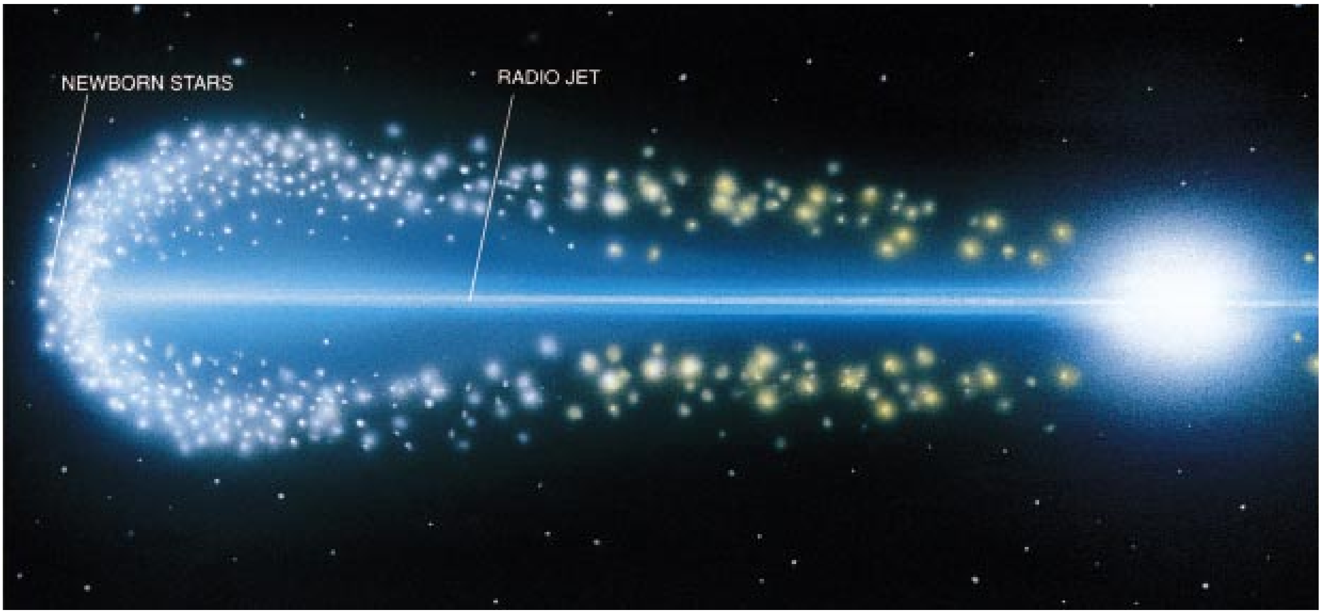
The powerful, easily detected radio emission produced by quasars and radio galaxies gives astronomers an effective way—at present, the only effective way—to locate galaxies at redshifts of two or higher. During the past decade, light detectors that incorporate charge-coupled devices, or CCDs, have revolutionized this line of inquiry by enabling astronomers to capture images of much fainter galaxies and to make spectroscopic measurement of their redshifts.

Throughout the 1970s, before CCDs became available, Hyron Spinrad and his colleagues at the University of California at Berkeley painstakingly examined the visible counterparts to the sources in the 3C catalogue. That effort revealed the first-known galaxies having redshifts greater than one. It culminated in the discovery of a radio galaxy at a redshift of 1.8, which for some time held the title of most distant known galaxy.

It is impractical to carry out time-consuming, high-sensitivity optical observations of the tens of thousands of fainter radio sources that are now known. During the past few years, several methods have been used to select the best, most distant candidates. Patrick J. McCarthy of the Carnegie Observatories in Pasadena, Calif., working with Spinrad and Willem J. M. van Breugel of Lawrence Livermore National Laboratory, has found



REDSHIFT AND DISTANCE are intimately related because of the expansion of the universe. The farther away an object is, the more its light has been stretched, or redshifted. In this graph, distance is expressed in terms of relative look-back time, the time that light took to travel from an object to the earth divided by the time that has elapsed since the big bang. Radio galaxies and quasars display bright emission lines that can be seen at redshifts of between four and five, when the universe was only about a tenth its present age.



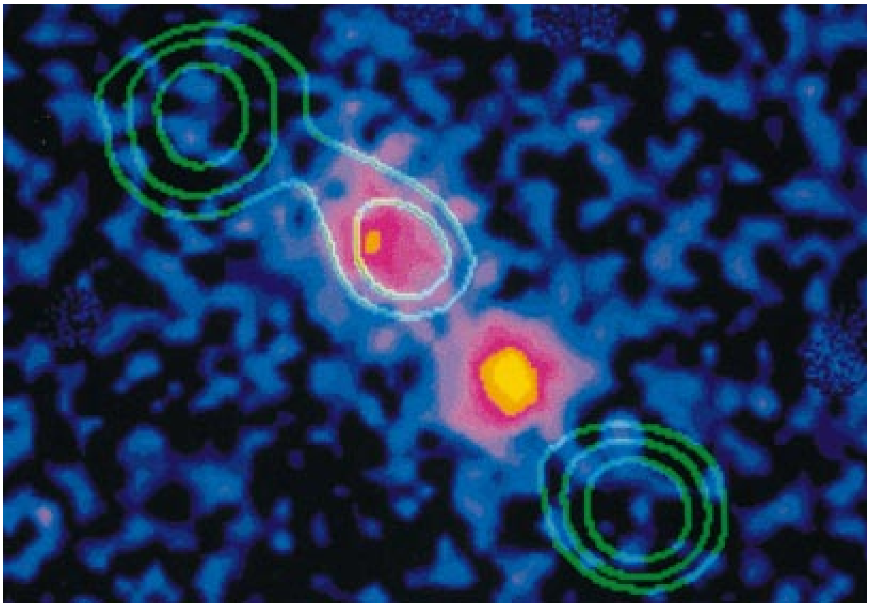
APPARENT ALIGNMENT of the shapes of the optical and radio components of radio galaxies may result from bursts of star formation. A two-sided jet of fast particles produced in a galaxy's central region propagates outward into the interstellar and intergalactic gas. As the front of the jet plows through the surrounding gas, it creates shocks that accelerate electrons to near-light speeds; these electrons generate radio waves as they race through the local magnetic field. The gas compressed by the shock cools to form clusters of stars that appear spread out along the direction of the radio source.

several galaxies lying at redshifts greater than two by concentrating on radio sources that have no bright optical counterpart. In a similar vein, Simon J. Lilly of the University of Toronto measured the optical colors of faint objects associated with the "1 Jansky" sample, a list of faint radio sources (several times fainter than those in the 3C catalogue) compiled using a radio telescope at Bologna, Italy. In 1988 Lilly, then at the University of Hawaii, reported discovery of a radio galaxy having a redshift of three.

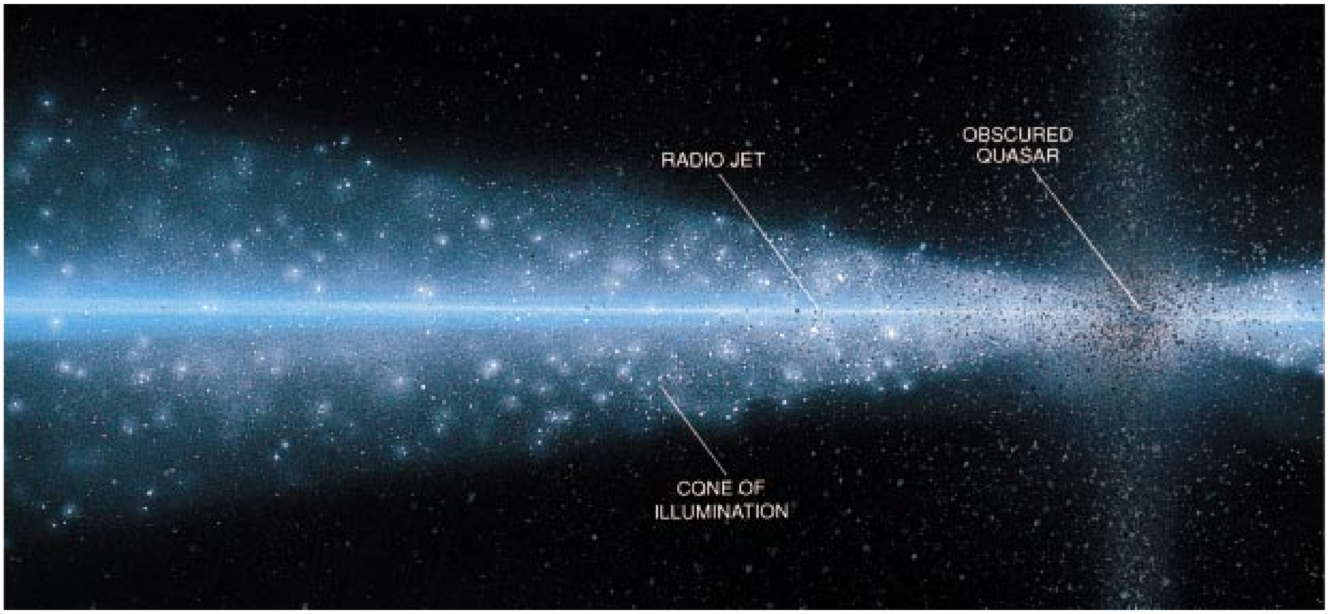
But nature has supplied another way to identify distant galaxies that has proved even more effective, one that is based solely on their properties at radio wavelengths. The spectral slope, or color, of the radio emission from an active galaxy correlates closely with its distance. The most remote objects have the steepest radio spectra—that is, their brightness falls off most rapidly from low frequencies to higher ones. Although the reason for the correlation between radio spectrum and distance is not yet fully understood, it serves as the empirical basis for a search method that works remarkably well.

We became the first researchers to take advantage of that correlation eight years ago, when we began to concentrate on the visible galaxies associated with radio sources that have particularly steep radio spectra. Among the first and most exciting objects we examined was 4C 41.17, which derives its name from the fourth Cambridge catalogue of radio sources. We identified the host galaxy connected with the radio source and determined its redshift to be 3.8. This source currently holds the title of most distant known galaxy.

Encouraged by that success, we continued our observations in collaboration with Huub Röttgering and Rob van Ojik of Leiden Observatory in the Netherlands and with several other colleagues. The work is progressing at an extremely rapid pace. Before we embarked on our project, not a single galaxy was known to have a redshift greater than two. So far our project has revealed about 35 galaxies at such high redshifts, bringing the total number known to more than 60. Our efforts are unveiling details of galactic evolution by showing how young, distant radio



REMOTE RADIO GALAXIES exhibit the alignment effect far more strongly than do more proximate ones. These two galaxies (*left* and *opposite page*), selected from a recent survey conducted by the authors and their collaborators, have



ALTERNATIVE MODEL proposes that the observed radio-optical alignment is caused by radiation scattered off electrons or dust particles. In this model, the radio galaxy contains a bright quasar that is mostly hidden from view by an obscuring shroud of dust. Light from the quasar can escape only along the axis of the radio jet. That cone of light illuminates material—either electrons or dust—and is scattered off this material and polarized by it. Because the light escapes along the direction of the jet, the observer sees the visible part of the galaxy oriented at the same angle as the radio source.

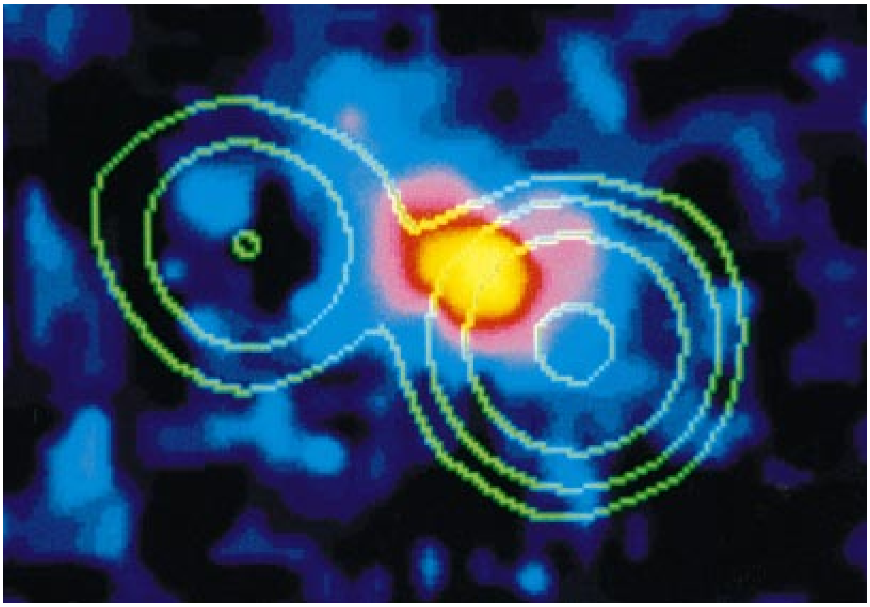
galaxies differ from more mature ones lying closer to the earth.

A remarkable property of giant elliptical galaxies (the ones that harbor the brightest radio sources) is the uniformity of their infrared luminosities. In 1984 Lilly and Malcolm S. Longair, both then at the University of Edinburgh, observed radio galaxies from the 3C catalogue in the infrared using the U.K. Infrared Telescope in Hawaii. They then constructed a graph of redshift versus infrared brightness out to a redshift of about 1.5. The resulting plot displayed a fairly neat, linear pattern, which seemed to imply that the intrinsic infrared luminosity of radio galaxies varies little over space or time.

When those observations were made, astronomers believed that the infrared emission in giant elliptical galaxies was produced by stars at least a few billion years old. The natural interpretation was that radio galaxies contain a sizable population of mature stars that all have fairly uniform properties. Lilly and Longair therefore hoped radio galaxies could serve as standard candles, objects whose absolute luminosity is known, so their apparent brightness can be used to measure accurately the size, age and geometry of the universe.

Improved observations have revealed that the situation is not that simple. Ten years ago most researchers thought radio emission was merely a useful tool for finding distant galaxies and that it did not influence the optical properties of the objects. That assumption, which was based on the fact that nearby giant elliptical galaxies look exactly the same whether or not they are strong radio sources, has turned out to be incorrect. New CCD images of the most distant radio galaxies show them to be lumpy and elongated, indicating that they are far from stable and uniform.

Those images have led to a tremendously exciting and unexpected finding. About six years ago, working independently, we and a group of researchers at Berkeley discovered that the axis of the radio emission from the galaxies lines up with the shapes seen when they are viewed in optical continuum radiation (that is, the entire band of visible



redshifts of about 2.5 (*left*) and 2.9 (*right*). The green lines show the contours of the radio emission; the false-color optical images were taken using the New Technology Telescope of the European Southern Observatory in Chile.

light, not just certain emission lines). That effect becomes noticeable in some radio galaxies having redshifts of about 0.5; at redshifts of one or more, most of these systems exhibit roughly aligned radio and optical morphologies. No comparable phenomenon is seen in nearby radio galaxies.

Much to cosmologists' regret, the observed radio-optical alignments undermine the use of radio galaxies as standard candles. The correlation between the prominence of the alignment and the galaxy's redshift strongly implies that the nature of the light from a radio galaxy depends strongly on the galaxy's distance. Furthermore, astronomers can no longer feel justified in assuming that sources selected because they are intense radio sources are, in every other respect, normal, representative galaxies. Only after the alignment phenomenon has fully been understood can we hope to disentangle optical distortions caused by the geometry of the universe from true changes caused by physical evolution.

Researchers have advanced two major hypotheses to explain the origin of the elongated visible morphology of these galaxies. One possibility is that the jet that powers the radio source sets off an enormous burst of star formation along its path; the other is that dust scatters radiation from a bright but obscured central energy source. If the former answer is correct, then the optical emission would be the light from the newborn stars. One of us (Chambers) and Stephane Charlot, then at the Space Telescope Science Institute in Baltimore, demonstrated that a burst of star formation that had been under way for a few hundred million years could indeed account for the optical and infrared colors of high-redshift radio galaxies. Such ages are also plausible for the radio sources.

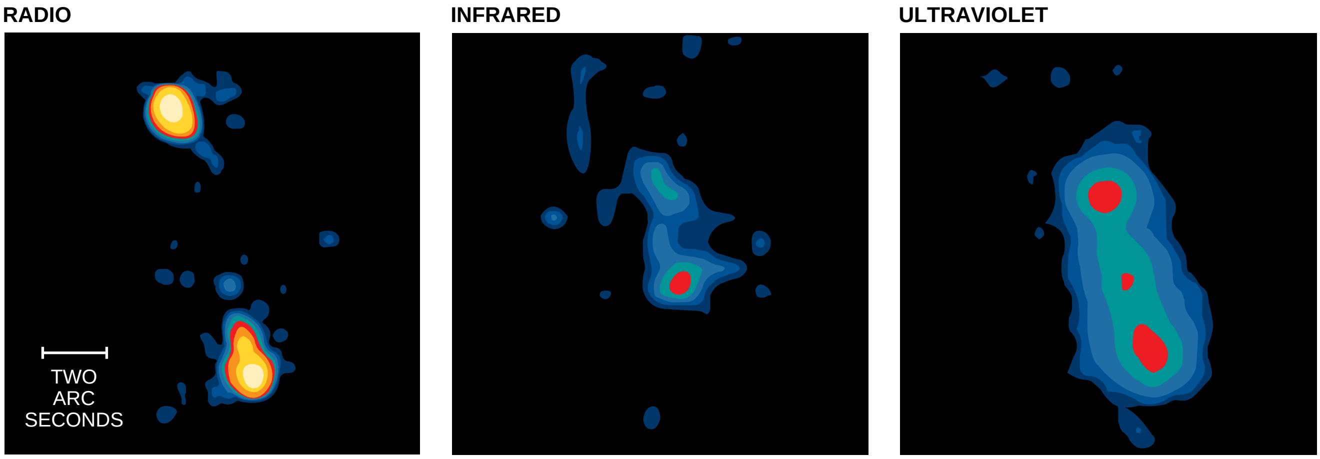
Theoretical work by Rees of Cambridge and by Mitchell C. Begelman of the University of Colorado and Denis F. Cioffi of the National Aeronautics and Space Administration also bolsters the idea of star formation. Their research suggests that shocks produced by the radio jet could compress clouds of gas surrounding the galaxy, allowing them to collapse into stars. David S. De Young of Kitt Peak National Observatory ran computer simulations of collisions between radio jets and clouds; his results confirm the plausibility of such a scenario.

Detailed studies of nearby radio sources offer additional observational support for the notion that jets might be able to trigger star formation. Although the radio source does not generally affect the optical appearance of nearby radio galaxies, observations now hint that jets can perturb the interstellar material within a galaxy. Timothy M. Heckman of Johns Hopkins University, van Breugel and one of us (Miley), using the Mayall Telescope at Kitt Peak, observed clouds of ionized gas lying along the radio sources in nearby radio galaxies. That finding suggests that the radio jets are interacting vigorously with the gas in these systems. One radio-emitting galaxy, the peculiar Minkowski's Object, shows what appears to be a newly formed dwarf galaxy located at a bend in the jet.

An alternative explanation for the radio-optical alignment was prompted by the observations of the optical polarization (the degree to which light waves are preferentially oriented in a particular direction) of 3C 368 and several other bright, aligned radio galaxies. A group led by Spirello di Serego Alighieri, Robert A. Fosbury and Clive N. Tadhunter of the European Southern Observatory and Peter J. Quinn of Mount Stromlo Observatory studied 3C 368 using a telescope in Chile; Michael Scarrott and C. D. Rolph of the University of Durham and Tadhunter conducted follow-up work at the William Herschel Telescope in the Canary Islands. The researchers found that the light from 3C 368 is highly polarized.

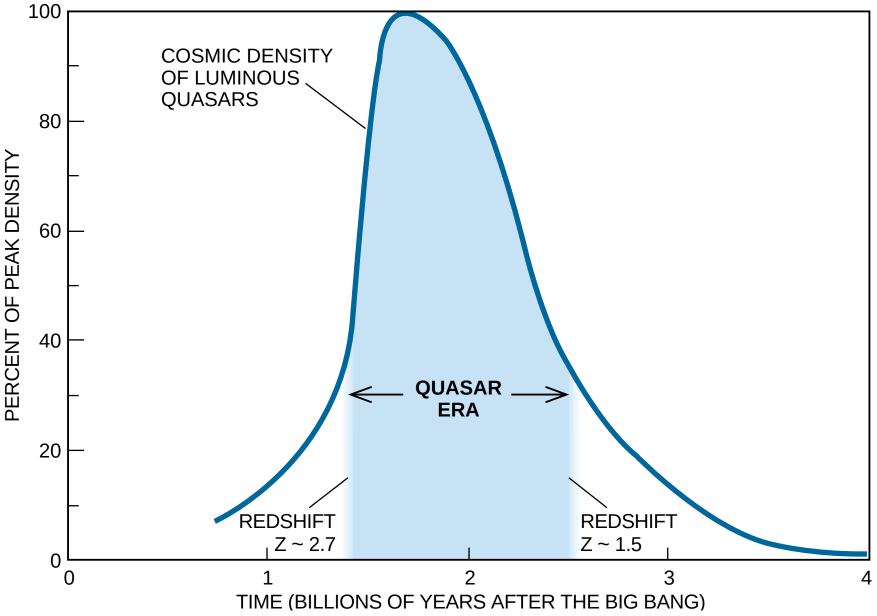
One of the easiest ways to polarize light is to scatter it. That fact led Tadhunter and his colleagues and, independently, Andrew C. Fabian of Cambridge to suggest that some of the light from the distant radio galaxies consists of scattered emission from a hidden quasar nestled in the galaxy's nucleus. Because the quasar's radiation is absorbed in every direction except along the radio axis, it cannot be seen directly. Like a searchlight passing through the fog, however, the quasar beam bounces off electrons or dust in its path, rendering it visible to terrestrial viewers. That scattered light would appear aligned along the radio jet.

Neither the starburst nor the scattering models can explain all the features of distant radio galaxies. The presence of polarization means that some light must be scattered. But electrons scatter all wavelengths of light equally well, so one would expect the scattered light to resemble the spectrum of a quasar, which it does not. Dust scatters blue light more efficiently than it does red and so could produce the strong color gradients that are observed. There is



DIFFERENT WAVELENGTHS capture subtly different aspects of the bright radio galaxy 3C 368; false colors denote intensity of radiation, from low (*dark blue*) to high (*light yellow*). Radio emission (*left*) is generated by high-speed electrons moving through the galaxy's magnetic field; a double-lobed structure is clearly evident. An infrared image (*center*) shows radiation emitted by stars and gas in the body of the galaxy. Ultraviolet rays having a wavelength of 3,727 angstroms come from oxygen atoms that have been disrupted and ionized (*right*). Note that all three images have similar orientations.

evidence that some radio galaxies display clear alignments between their radio and infrared emission, however, and a dust model has difficulty producing enough infrared scattering to account for this effect. In any case, dust consists of heavy elements that form only in the interior of stars, so it could be present only if some stars have already formed along the radio axis. A composite picture of distant radio galaxies that includes both star formation and scattering along the radio axis therefore seems most plausible.



QUASARS AND RADIO GALAXIES were nearly 1,000 times more abundant two billion years after the big bang than they are now. The reason for the rapid rise and decline of the active galaxy population is a mystery, one that may hold important clues about the formation and early development of massive galaxies.

Attempts to decipher the processes responsible for the radio-optical alignment effect are already leading to the development of more sophisticated theories about the early evolution of radio galaxies. Further advances will depend on finding additional radio galaxies at very high redshifts. We and a number of our colleagues are working hard to do just that.

Some intriguing preliminary results have emerged from our follow-up studies of 4C 41.17. Last year, in collaboration with van Breugel and F. Duccio Macchetto of the Space Telescope Science Institute, we used the *Hubble Space Telescope* to observe 4C 41.17. The resulting image has an angular resolution roughly 10 times better than the previous ground-based photograph. This sharp picture shows the inner region of this galaxy to have an irregular, clumpy form. Those clumps may represent gas clouds illuminated by a central quasar, or they may be giant star clusters caught in the act of coalescing. Analysis of the spectrum of 4C 41.17 may determine which of these explanations is correct and hence could reveal the mechanism that produces the radio-optical alignments.

Optical and radio telescopes could detect objects like 4C 41.17 at redshifts of about six, if such remote, young galaxies exist. Finding and examining radio galaxies at ever greater redshifts will help settle many profound questions about how the universe was born and how galaxies formed. Sensitive images and spectra of regions surrounding those galaxies will enable astronomers to search for nearby companions or clusters of galaxies. Studies of the galaxies' colors will yield information about the stars they contain and hence about how soon after the big bang those stars began to shine. Related observations of shapes and motions within the galaxies may establish whether these objects are being seen while they are still in the process of collapsing from primordial clouds of hydrogen and helium gas.

Furthermore, spectral analysis of extremely distant radio galaxies enables astronomers to observe whatever may lie along the line of sight between those galaxies and the earth. Intervening gas clouds or other galaxies, for example, could produce detectable absorption lines in the radio galaxy's spectrum. Those lines can reveal information about the shape, composition and kinematics of the intervening objects, as well as their distance. Because radio galaxies, unlike quasars, are spatially extended, they can serve as valuable probes for investigating closely separated lines of sight a few hundredths of a degree apart.

Simply compiling a more complete tally of distant radio sources will clarify how many quasars and radio galaxies existed during the first couple of billion years after the big bang and how the density of those objects evolved over time. As with the extinction of dinosaurs on the earth, the stunning decline of the active galaxy population as the universe has aged signals a dramatic change in the celestial environment. Many researchers are now conducting a census of distant radio galaxies as a function of their redshift and absolute radio luminosity. Detailed comparisons of the population densities of quasars and galaxies at redshifts greater than two may elucidate the processes responsible for exterminating the species.

Over the next decade, an impressive arsenal of instruments will facilitate these investigations. At the end of this year, NASA plans to correct the optics of the *Hubble Space Telescope,* improving the sensitivity with which it can observe distant radio galaxies by about a factor of five. A new generation of large ground-based optical telescopes, such as the European Southern Observatory's Very Large Telescope and the two 10-meter Keck telescopes in Hawaii, will be able to map faint objects that have eluded detection thus far. These tools hold out the promise that within the next few years astronomers will greatly expand their understanding of a universe that has been 15 billion years in the making.

FURTHER READING

4C 41.17: A Radio Galaxy at a Redshift of 3.8. K. C. Chambers, G. K. Miley and W.J.M. van Breugel in *Astrophysical Journal,* Vol. 363, No. 1, pages 21–39; November 1, 1990.

High Redshift Radio Galaxies and the Alignment Effect. K. C. Chambers and G. K. Miley in *Edwin Hubble Centennial Symposium: Evolution of the Universe of Galaxies.* Edited by R. G. Kron. Astronomical Society of the Pacific, 1990.

Distant Galaxies. G. K. Miley in *Proceedings of the ST-ECF/STSCI Workshop on Science with the Hubble Space Telescope: ESO Conference and Workshop Proceedings,* No. 44. Edited by P. Benevenuti and E. Schreier. European Southern Observatory, 1992.

Hubble Space Telescope Imaging of Distant Galaxies: 4C 41.17 at $z = 3.8$. G. K. Miley, K. C. Chambers, W.J.M. van Breugel and F. Macchetto in *Astrophysical Journal,* Vol. 401, No. 2, Part 2, pages L69–L73; December 20, 1992.