VERY LARG

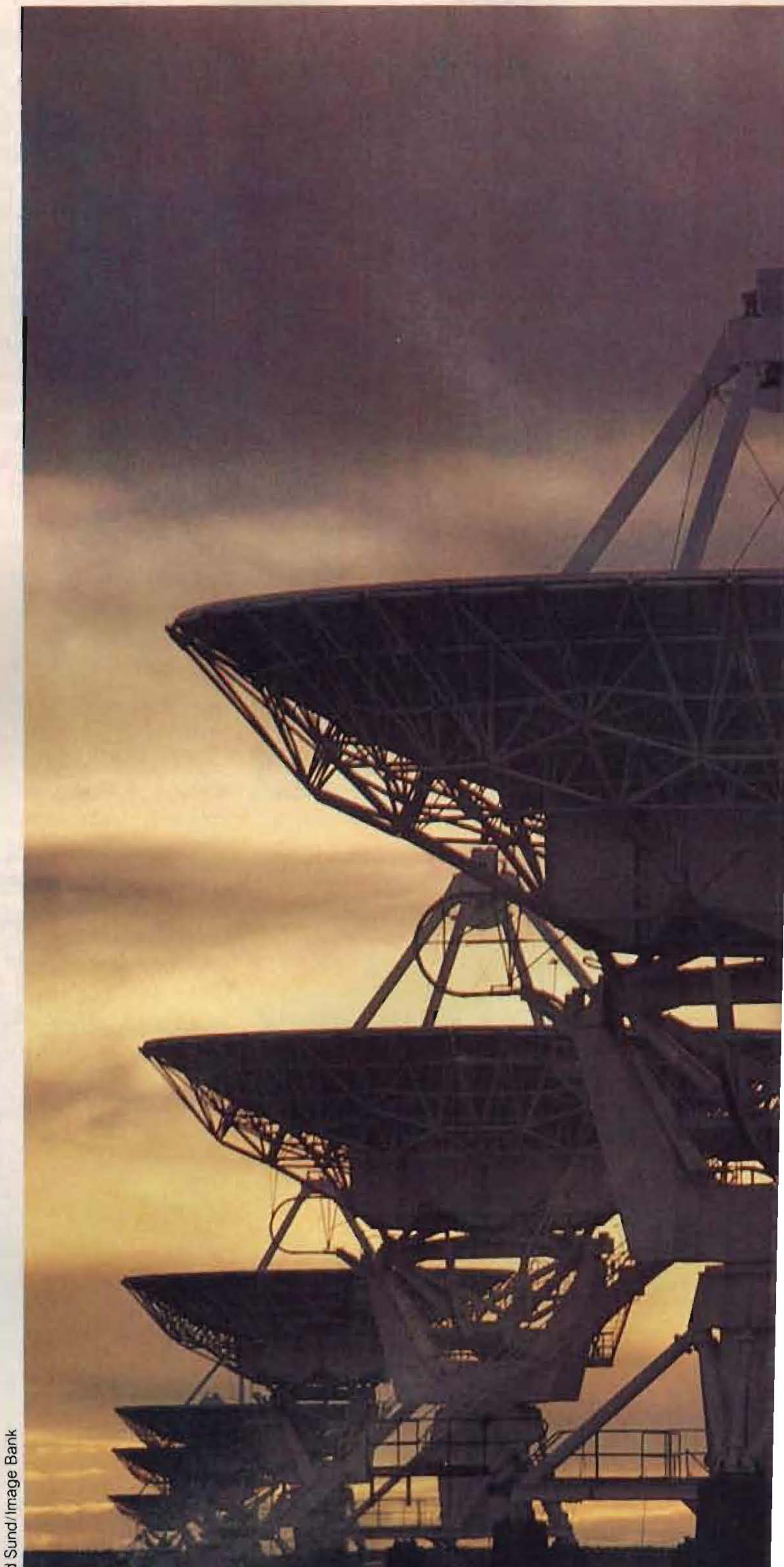
In the hearts of galaxies lurk strange and powerful beasts. Astronomers hope to catch them with worldwide nets of radio telescopes.

by Marcia Bartusiak

Even at 55 miles per hour, the desolate terrain seems to pass by in slow motion. Only an occasional group of piñon pine on the side of a hill or, farther off, the stark profile of an erosion-sculpted mountain breaks the monotony.

But suddenly, after driving over a rise on Route 60, a few dozen miles west of Socorro, New Mexico, the weary traveler will come upon a sight unlike any other on Earth: 27 dishlike antennas lined up for miles over the flat, desert Plains of San Agustín. Airline pilots who fly over the ancient, mile-high lake bed have dubbed this gigantic Y-shaped configuration the mushroom patch. But to astronomers it is simply known as the VLA—the Very Large Array that for several years now has served as radio astronomy's premiere eye on the universe.

Twenty-four hours a day, seven days a week, the VLA's majestic white dishes move in unison, like a mechanized version of the Rockettes, to collect the radio waves sent out by the universe's myriad celestial inhabitants. On one day, the antennas might trace the wispy outlines of a gas cloud in the dusty spiral arms of our Milky Way to see how its molecules tumble and collide, leading astronomers to the birthplace of new stars. The next day, a VLA computer appropriately named the Boss could order the 82-foot-wide dishes to point toward a supernova and snap a "radio picture" of the debris racing away from the



Harald Sund/Image Bank

Using radio dishes that stand 100 feet high and weigh 235 tons apiece, the Very Large Array near Socorro, New Mexico, tunes in on galaxies some millions of light-years away.

E ASTRONOMY

mighty stellar explosion.

Often, however, astronomers will train the multiple antennas on some very special members of the celestial zoo. Take NGC 6251. In regular optical photographs, this distant elliptical galaxy appears ordinary, even boring. But the VLA's keen radio eyes reveal that the core of NGC 6251 is actually shooting a monstrous river of energy hundreds of thousands of light-years into space, not unlike a jet of water streaming out of a fire hose.

Stalking the dynamos at work inside these violent galaxies was a major impetus for many countries to construct extensive radio telescope arrays during the last two decades, including the sprawling VLA. And the quest continues. Even as the VLA was coming on line during the late 1970s, Great Britain was setting up a system called MERLIN. This Multi-Element Radio-Linked Interferometer Network combines signals from half a dozen radio dishes scattered about southern England's scenic countryside.

To sharpen their eyesight even further, astronomers have been ingeniously linking radio dishes across the United States and Europe. Such an intercontinental array mimics the capability of an antenna thousands of miles in diameter—as wide as the Earth itself. In this way, astronomers can make out details a thousand times finer than can any ground-based optical telescope.

The most recent findings from these arrays have reinforced a view of the heavens that has been evolving since the 1950s: Our universe is a place where violence, not serenity, reigns supreme. Not even the most farsighted Victorian scientist could have imagined such a tumultuous cosmos.

At the turn of the century, astronomers were still carrying out the tradition initiated by Galileo's first gaze upon the heavens. From lonely mountaintop posts, they photographed twinkling bits of light entering their telescopes, blithely unaware that the cosmos was unveiling quite a different picture in waves of electromagnetic energy other than visible light. Karl Jansky, an engineer for Bell Telephone Laboratories, finally broke this bond to the optical window in the early 1930s when he built a crude antenna amid New Jersey's potato fields to investigate disruptions in transatlantic radio-telephone communications. Accidentally, Jansky detected

James A. Sugar/Black Star

"Mushroom patch": The VLA's 27 antennas can be rolled along tracks to change their configuration. Above, each arm of the "Y" extends about half a mile; this offers a wide-angle view of space. In its most expanded pattern, with each arm reaching 13 miles, the array gives a more closeup view.

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radio signals emanating from the center of the Milky Way.

Although Jansky didn't know it at the time, some of the signals he picked up were being emitted from violent streams of charged particles in space. Just as an oscillating electric current within a broadcast antenna releases waves of radio energy into the air, these energetic "plasmas" also broadcast radio waves, which, with the right antenna, can be detected and analyzed.

After World War II this new branch of astronomy burgeoned, with antennas sprouting around the globe. Powerful, blobby regions of radio emissions were located all over the sky. But what heavenly objects were sending out these signals? Unlike optical telescopes, radio dishes of the time had a very myopic, out-of-focus view of the heavens. According to VLA astronomer Edward Fomalont, there were hundreds of visible objects in the neigborhood of each fuzzy radio region—and no way to know which optical image matched up with the radio signal. This is because a single radio dish has a difficult time zeroing in on the exact position and extent of a source.

How much detail a telescope can make out basically depends on how large its collecting surface is compared to the waves of electromagnetic energy being gathered to detect the celestial object of interest. The lenses and mirrors in an optical telescope are gargantuan to a visible light wave, which is only a few hundred-thousandths of an inch long. This means optical astronomers can resolve, or discern, galaxies that cover a mere 3/10,000 of a degree in the sky, less than 1/1,000 the width of the moon's disk as seen from Earth. That's enough resolution to read the label on a tennis ball bouncing in a court several miles away.

But radio waves are hundreds of thousands of times longer than visible light's electromagnetic undulations, which means a radio dish has to be many miles wide to match optical resolutions. Thus, for a while, radio astronomy's usefulness seemed limited—until British and Australian researchers turned to an old yet clever means of sidestepping that resolution barrier.

They began connecting pairs of dishes that stood up to a few miles apart. Via cables or radio links, the waves received by each antenna were sent to a central processor and combined. The technique is known as interferometry because it analyzes how the waves from each antenna "interfere" once they're added together. If the two waves are in step when combined, they add up to a bright strong signal. But if they are not in step, they destructively interfere and cancel out each other. As the two antennas track their target, a pattern of peaks and troughs emerges. Astronomers, or their computers, can translate these varying radio intensities into a rough image of the source.

The result: a crude substitute for a miles-wide antenna. Though not as sensitive at detecting weak signals, because the collecting surface doesn't cover the huge area that a true miles-wide antenna would, a two-dish interferometer can resolve tinier details than either of its dishes can separately.

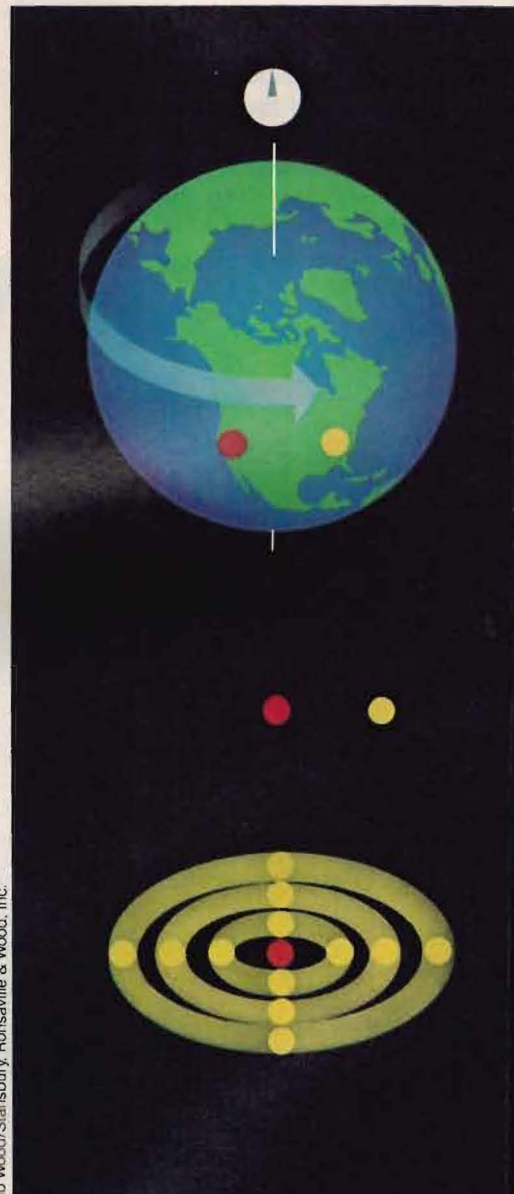
Starting in the 1950s, this newfound acuity finally enabled astronomers to pin down the celestial objects sending out those indecipherable radio squeals. In some cases, large amounts of radio energy appeared to be coming from stars whose optical light images looked rather prosaic. "Optical astronomers had seen them in photographs before but said, 'Oh, a faint blue star, so what,'" explains Alan Bridle, staff scientist with the National Radio Astronomy Observatory headquartered in Charlottesville, Virginia.

But the intense radio signals coming out of those faint blue dots forced a second look. They weren't stars, it turned out, but rather cosmic denizens located at the very fringe of the known universe—millions, even billions of light-years away. Today, these quasi-stellar objects, or quasars, are generally thought to be the brilliant cores of newly born galaxies, each spewing the energy of billions of suns out of a space no bigger than our solar system.

The quasars weren't alone. Astronomers had been finding that thousands of elliptical galaxies were also emitting copious amounts of radio energy. These emissions were virtual screams of radio noise, each millions of times more powerful than the Milky Way's paltry radio output. Astronomers realized they had identified another new species in the celestial zoo: radio galaxies.

The structure of these galactic titans was quite bewildering. Combining the optical image with maps of the radio signals, astronomers saw that the visible part of such a galaxy is caught between two immense lobes of radio emission. Looking like a pair of giant water wings, these lobes stretch out for hundreds of thousands of light-years beyond the visible galaxy's edge. "At first," says Fomalont, "it seemed like some kind of explosion had shot these two clouds out of the galaxy. But no one could explain how these energetic lobes could still be hanging around after tens of millions of years."

"We were becoming aware," adds Bridle, "that these objects were emitting energy by processes not directly connected with stars." In fact, it would take 100 billion stars to energize the lobes of the most powerful galaxies via



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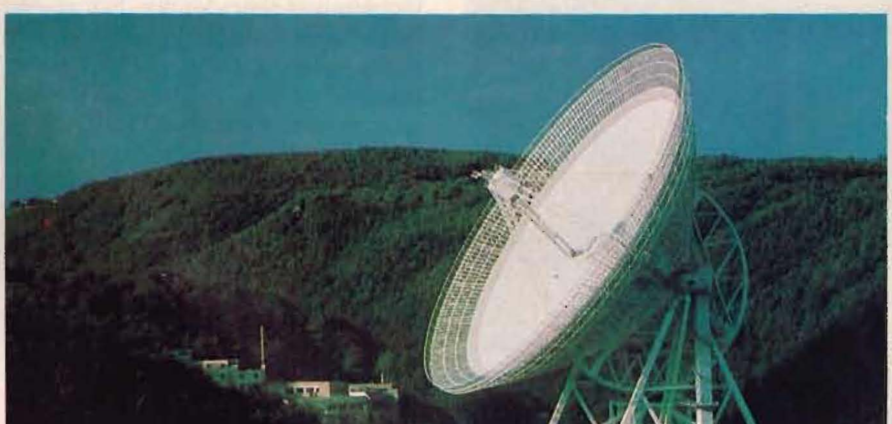


Science Photo Library

Some 300 feet across, the Effelsberg dish near Bonn is the world's largest steerable radio antenna. A ring of wire mesh cuts wind pressure that might distort the dish.

"Each galaxy was so active because it contained a monster—and things were being fed to the monster."

How to build a superdish

In 1974 British astronomer Martin Ryle was awarded the Nobel Prize for his ingenious use of the Earth's rotation to synthesize a large radio telescope from a few small ones. Consider two dishes on either side of the United States, above. As the Earth spins on its axis, each dish appears to trace an elliptical path relative to the other. If the red dish is set at the origin of an arbitrary coordinate system, then the yellow dish sweeps out one-quarter of an ellipse around it every six hours, as shown below each globe. More dishes, placed at varying distances between the first two, will trace different sized ellipses. By letting the Earth's spin sweep the antennas around, an astronomer—with the aid of a computer to keep track of the coordinate system—can build up an immense imaginary radio telescope ring by ring, as shown at left. Because the synthesized dish has a diameter so much larger than the individual dishes, it can discern much finer details. Following this strategy, the VLA, a compact array using 27 movable dishes, can sweep out a receiving area 21 miles across. Very long baseline networks, with fixed dishes located continents apart, can synthesize antennas of global scale.

simple thermonuclear fusion, the standard means by which stars release energy. "Each galaxy was becoming active," says Bridle, "because (a) it contained a 'monster' and (b) things were being fed to the monster."

But what was this celestial beast, and how was it transferring such titanic energies out to intergalactic space? VLA director Ronald Ekers, who got his start working with one of Australia's first two-dish interferometers, says it was these questions, more than anything else, that spurred countries like Great Britain, Australia, the Netherlands, and the United States to build ever-bigger interferometers, with more dishes and longer spacings, or baselines, between antennas for increased resolution and better images.

One of the most ambitious facilities built to date is the VLA, which finally scaled that Mount Everest of radio astronomy: the development of an interconnected array that could quickly and easily match the resolution of optical telescopes. At the same time, the total collecting surface of the 27 antennas makes the array sensitive enough to detect the signal from a one-watt citizens-band radio on faraway Pluto.

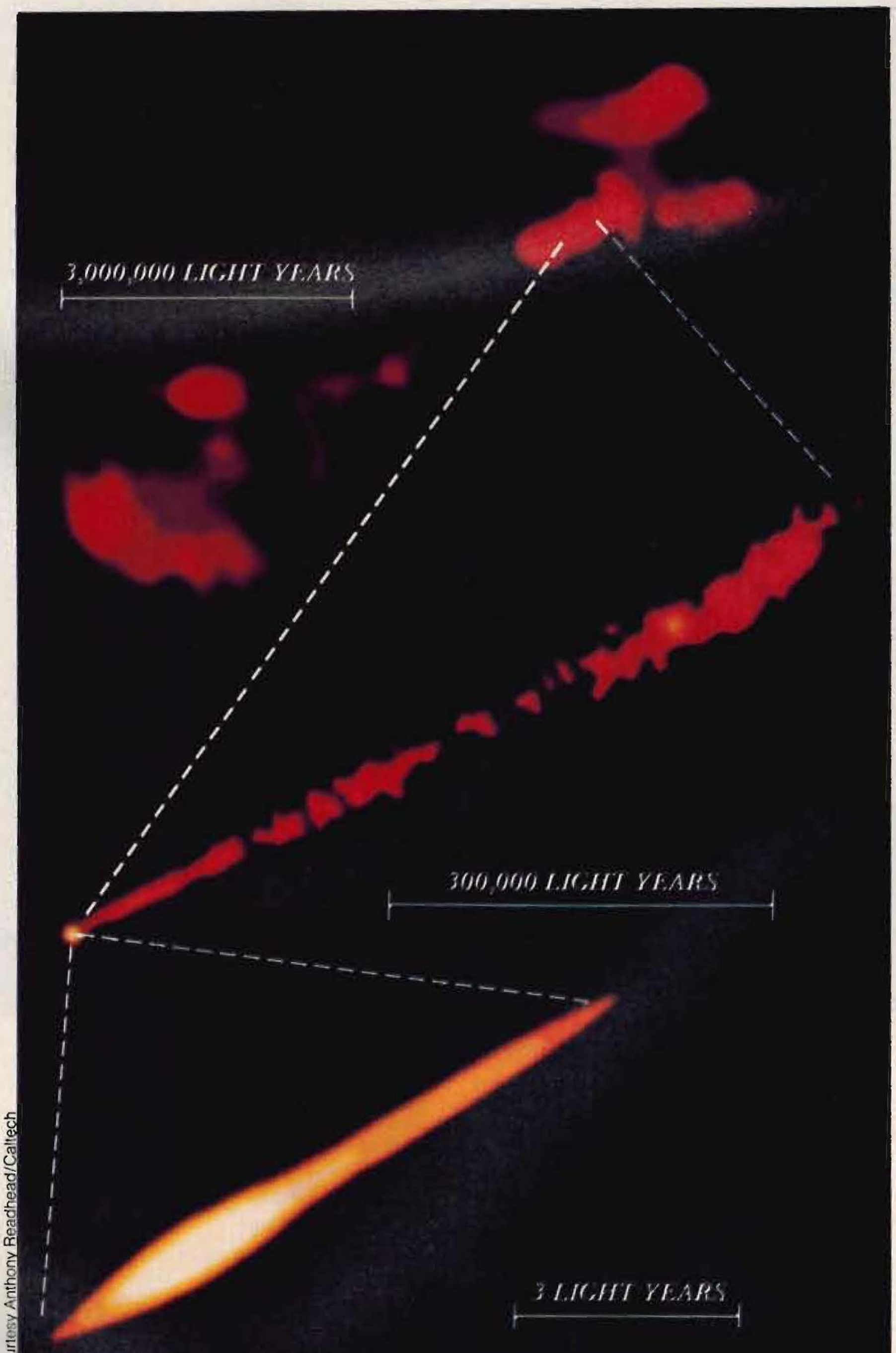
"Advances in computer technology really made this all possible," explains Ekers. "I think of the computer as part of the instrument." And for good reason. Every second, VLA computers located in the main control building must digest a million bits of data arriving from the network via a 40-mile-long system of waveguides—two-inch copper-lined steel tubes—buried beneath the desert plain. A typical 12-hour observation can take up three computer tapes, enough digital information to fill some 200 books.

Each datum helps define the intensity of the radio source at a certain point in the sky. Once these myriad bits are processed and displayed on a computer graphics terminal, a color-coded radio picture of the source emerges. Other interferometers have done this before but never so efficiently.

Another strength of the VLA is its ability to act like a zoom lens. A few months at a time, the antennas are crowded in, each arm of the Y no more than half a mile long; this provides a wide-angle view, perhaps to trace the gas clouds in a nearby galaxy. But to zero in for a closer look, the antennas are periodically moved along railroad tracks out to greater distances, up to 13 miles. To a source in the sky, this configuration appears to sweep out a dish larger than Washington, D.C., as the Earth slowly turns on its axis.

That imaginary dish helped astronomers confirm what some theoretical astrophysicists, like Britain's Martin Rees and Caltech's Roger Blandford, had already suspected: that a sort of umbilical cord must be running from the core of a radio galaxy or quasar out to its lobes, continually resupplying the puffy blobs with energy. Indeed, maps made with the VLA clearly show these cords: thin beams of energetic, radio-emitting plasma shooting out of the cores of galaxies, some at speeds of tens of thousands of miles per second.

Like galactic psychologists, VLA astronomers have spent the last several years analyzing the personalities of these "cosmic jets," as they've been tagged. Some jets, like the two emanating from the center of 3C 449—an elliptical galaxy 200 million light-years distant—can be relatively calm. "Such jets are usually seen in the less energetic radio galaxies," explains Richard Perley, who in 1979 trained the VLA's



courtesy Anthony Readhead/Caltech

Three false color radio images of NGC 6251, a galaxy 400 million light-years away: Top shows overall shape, especially the lobes. Middle is a close-up of a hot plasma jet being expelled at 3,000 feet per second from the galaxy's core. Bottom focuses in on the core, where the white inner jet probably is spewing away from a black hole region.

Like galactic psychologists, astronomers analyze the personalities of these "cosmic jets."

antennas on 3C 449. "They have a lower velocity, and sort of diffuse away— like smoke rising out a chimney, becoming unstable, and breaking up."

But Perley's particular favorites are the jets with "punch power," as he puts it. These energetic beams spew from the galactic centers thinner, straighter, faster, and farther than the calm types. "An elliptical galaxy known as Cygnus A is a classic example, a source that we've resolved in marvelous detail." What Perley and his colleagues see is one of nature's most wondrous fireworks shows. Like a welding torch, Cygnus A's jets bore through the thin gases found in intergalactic space "until they hit a more dense, undisturbed region of gas, somewhat like the stream from a fire hose coming up against a brick wall," says Perley. In computer-generated pictures, this area appears at the end of the jet as a glowing red hot spot of intense radio emission. "From this point," continues Perley, "the particles fly off, filling up the lobe region."

What keeps such a cosmic river flowing? Theorists suspect a unique kind of "engine" hidden deep within the bowels of each radio galaxy or quasar. Its design specifications are pretty stringent. For the most active galaxies and quasars, this mysterious engine must be stable (the jets maintain their orientation for millions of years), extremely compact (daily fluctuations in core brightnesses suggest the engine is no bigger than our solar system), and able to eject prodigious amounts of energy at nearly the speed of light. Thermonuclear fusion, the simple fusing of atomic nuclei that drives every star in the universe, is not the answer. What is much more efficient as an energy generator is this: accelerating matter to near-light speeds by throwing it down a deep gravity well.

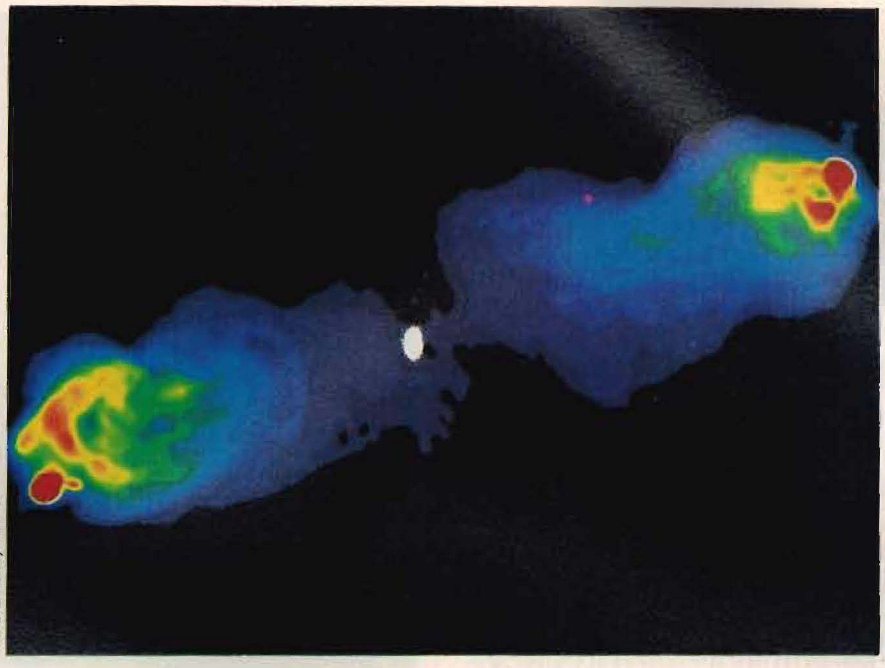
Presently, the most popular candidate for that gravitational pit is a spinning, supermassive black hole that formed from the collapse of up to a few billion suns. The existence of this monstrous celestial creature is based only on circumstantial evidence, so Blandford discusses the model with a note of caution: "It's easy to get carried away with this idea. One must remember that we're drawing inferences from fragmentary evidence, rather like an archeologist trying to recreate an entire civilization from a few scraps of broken pottery."

For now, the cosmic shards suggest that stars and gas in an active galactic center are sucked in by the powerful gravitational pull of a black hole, forming a kind of standing whirlpool around the hole. Some believe that enormous amounts of energy are released as matter in this whirlpool spirals into the black abyss and is ripped apart by the gravitational tug-of-war.

If the hole is fed more than it can chew, excess gas that has not yet reached the point of no return might be getting deflected—squeezed out like toothpaste from the top and bottom of the whirlpool. Undergoing violent acceleration, charged particles among these magnificent jets of matter could broadcast the kind of radio signals astronomers have seen in and around some galaxies.

"But another very attractive way to supply the power," suggests Blandford, "is not to rely on the energy of the infalling gas but rather to tap the spin energy of the hole itself. In effect, to create a cosmic dynamo."

In this scenario magnetic lines of force, the same forces that line up iron filings around a bar magnet, surround the black hole and whirl around with its rotation. Because of the tremendous spin of the black hole, the magnetic field lines come out of the north and south poles coiled like streamers around a Maypole, forming a narrow channel that captures nearby charged particles. Like a gigantic turbine in a cosmological power plant, these spinning fields generate more than a million trillion volts of electrical potential, accelerating the particles out along the magnetic channel to near the speed of light. Again, such acceleration triggers the particles to emit radio waves. "And the spinning black hole acts like a gyro-



Richard Perley/NRAO

Electrons shoot out of the core of Cygnus A, emitting intense radio signals where they slam into surrounding gases, shown as red hot spots. Diffuse lobes churned up in the turbulence give off less intense signals, shown in blue. The radio galaxy extends far beyond its visible image, marked by the small white blob in the center.

scope," says Blandford, "aligning the jets along its stable axis."

For the moment, however, the black hole hypothesis is sheer conjecture. Even as the VLA was merely a sketch on an engineer's drawing board, astronomers knew that they needed interferometers with baselines of thousands of miles to delve into the very hearts of these active galaxies to see directly what was brewing. It's a matter of simple geometry: The smaller the source, the wider apart the antennas have to be to resolve the minute details. For a while the situation looked hopeless, since a cable- or radio-linked system cannot easily span such distances.

But by the late 1960s, advances in atomic clocks provided the means to start pursuing that ever-elusive engine. At that time, groups in the United States and Canada began experimentally to record the signals at widely separated radio telescopes simultaneously on magnetic tape and to ship the tapes to a central computer, where they were combined. An extremely accurate atomic clock stationed at each antenna was the guarantee that the recordings would be synchronized to within a millionth of a second; any less precision would lead to a unintelligible picture.

It wasn't hard to come up with a name for this technique. "If a few dozen miles is long," says Caltech radio astronomer Marshall Cohen, "then several thousand miles is very long." Today, Very Long Baseline Interferometry investigators regularly borrow time on half a dozen single dishes scattered about North America and Europe. Such an extended network acts like an antenna that stretches across the globe.

Coordinating six or more diverse telescopes—the record is 18—can sometimes become an administrative and instrumental nightmare, but often the VLBI observation is fairly routine. Informal committees on both sides of the Atlantic schedule the telescope time; once each observatory in the network receives the schedule, staff members can take care of the simultaneous tracking, timing, and taping. "VLBI astronomers could actually observe for years and never see a radio telescope," says Cohen, one of VLBI's founding fathers. "You can't be everywhere, so there's no need to be anywhere!"

Instead, what VLBI users have to deal with are trillions of bits of raw data that must be correlated and processed into an image, a task that can take weeks; the VLA, on the other hand, with its automatic and efficient setup can create images in an hour. "With VLBI, if you fill up one computer tape every four hours and observe for 12 hours using six telescopes, that means 18 tapes in all," points out Cohen's colleague Stephen Unwin. But Unwin isn't complaining. "It's quite easy now to get angular resolutions 500 times keener than the VLA's."

That means that while the VLA and European arrays map overall structure of the radio galaxies, VLBI can look out to the farthest reaches of our universe and discern the finer details in galactic cores and quasars spanning only a few light-years in width—smaller than the separations between many stars in our galaxy. That's like being able to read a newspaper in St. Louis from New York City.

VLBI's penetrating gaze has even closed in on the very fountainheads of some jets and seen streams break off and move out into space. In fact, more than half a dozen quasars appear to be ejecting blobs of matter at velocities many times greater than the speed of light, an apparent violation of Einstein's special theory of relativity.

"There's actually nothing very strange about it," says Unwin, who with several colleagues used a network of five telescopes stretching from California to West Germany to monitor a quasar called 3C 345. Between 1979 and 1981 they saw two knots break off from its bright core and race away at what appeared to be 12 times the speed of light. But Einstein wasn't wrong, according to the theorists. Such superluminal motion is an "optical illusion" that occurs when the jets are pointed almost directly toward Earth and the material streams out at velocities very close to light speed.

Finally, as more dishes are added to the VLBI network and better receivers are incorporated, several radio astronomers, like Caltech's Dayton Jones and Joan Wrobel, are peering into the fine structure of weaker, less flamboyant radio galaxies. And intriguingly, the mild-mannered ellipticals they've observed "look exactly like all the strong radio sources that are studied with the VLBI," says Jones. "They basically have an extension at least six light-years long coming off a bright core."

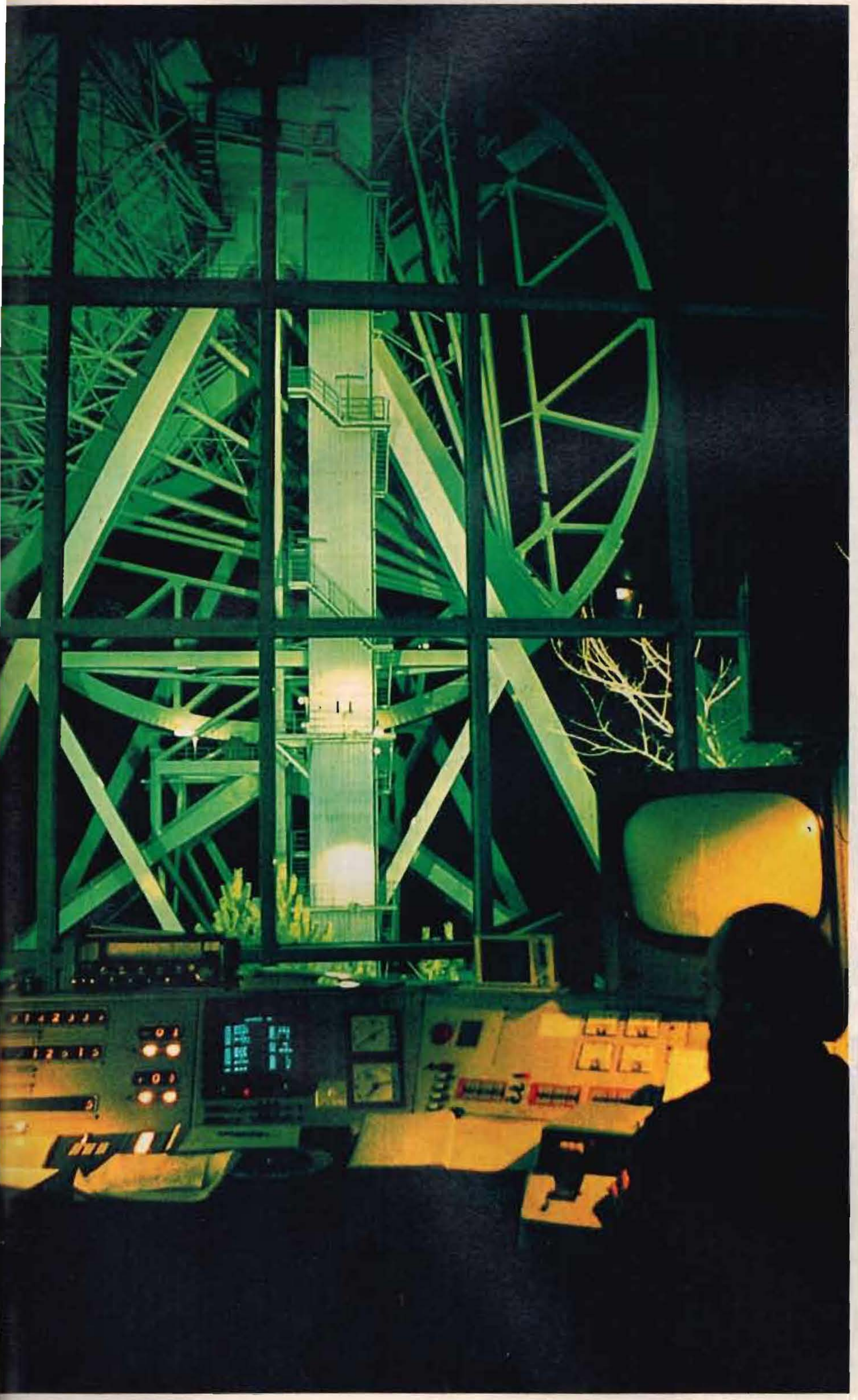
This hints that these weak emitters may have the same central engine as the superluminal 3C 345's in our universe, only one with a lot less horsepower. Perhaps they're the glowing embers of quasars in their senior years. For that matter, quasars may be the violent early stages of typical radio galaxies. "There's even something funny going on in the middle of our own galaxy," says Blandford, referring to clues of spiral-shaped jets and an intense object in its center. "That encourages the belief that the 'engine,' although maybe in a more dormant form, exists in the center of most galaxies."

But answers won't be forthcoming, say many radio astronomers, until they can overcome the awkwardness still inherent in the current VLBI system: borrowing time when they can on many different decades-old radio telescopes not designed to be part of a uniform array. Because of these limitations, both American and Canadian astronomers are anxiously awaiting the construction of permanent VLBI networks across each of their countries.

Barring congressional budget cuts, the U.S. system, to be called the Very Long Baseline Array, is scheduled to be completed by 1989. It will consist of at least 10 identical VLA-type antennas

In the control room of the Effelsberg radio telescope, engineers sometimes coordinate observations with stations in California, West Virginia, and elsewhere as part of a global interferometry network.

"Maybe, just maybe, we'll finally get a look at the black hole region itself."



dedicated to serving only the network and located for maximum image coverage at sites in Hawaii, Washington, California, Arizona, New Mexico, Iowa, Texas, Massachusetts, and Puerto Rico. The movements of every dish will be controlled by a master computer in Socorro. In many ways, the system will act as an extension of the VLA.

This state-of-the-art transcontinental array will begin operating with the ability to gather wavelengths as short as seven millimeters. "The shorter the wavelength," explains Cohen, "the deeper and deeper one can probe the central cores. It's like using X rays to look inside a grapefruit to see how big the seeds are. Maybe, just maybe, if we can get down to three millimeters we'll finally get a look at the the black hole region itself." Or perhaps some other beast as yet undreamed of.

With ground-based interferometers limited to the width of the Earth, even more resolving power can be had if VLBI takes to space. One idea is to unfurl a large antenna from the space shuttle to demonstrate the principle; in a more ambitious proposal, astronomers would like NASA and the European Space Agency to launch a permanent spaceborne antenna, a mission they've dubbed Project Quasat. With an orbit extending up to 10,000 miles above the Earth's surface, this 50-foot-wide dish could increase current VLBI resolutions at least three times over.

In many ways, the sophisticated computer facilities, massive instrumentation, and team effort required in these endeavors has moved radio astronomers into a realm more often associated with high-energy physicists and their gigantic atom smashers. "It seems that the further you get away from the scale of your sense perceptions, the more technology you need to make it understandable," notes Bridle.

"But then," he adds, "you can't be Galileo forever." S

Marcia Bartusiak is currently working on Thursday's Universe, *a book about the frontiers of astrophysics.*