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# *Relativistic Jets and the Most Powerful Radio Sources in the Universe*

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## Summary

Relativistic jets, which are beams of particles and magnetic fields emitting synchrotron radiation that emanate from black holes at the centers of galaxies and quasars, have been one of the most exciting discoveries made at the Very Large Array (VLA) operated by the National Radio Astronomy Observatory (NRAO).

The VLA is an array of 27 antennas, each 25 meters in diameter, distributed in a Y-formation with two branches 21 kilometers long and one branch 19 kilometers long. Astronomers can use it to study relativistic jets that generate intense natural radio sources (or transmitters). These sources, associated with regions hundreds of thousands of light years across, are the most powerful in the universe in energy output.

In his lecture, Bridle describes how consecutive advances in imaging techniques for radio astronomy have uncovered the properties of the powerful radio sources, culminating in the discovery at the VLA that many of these sources contain radio emitting jets. He then describes some of the NRAO's research on these jets, and discusses the jets' physical properties. He concludes with an outlook for the future: the NRAO's Very Long Baseline Array (VLBA) is to be completed in the early 1990's. The VLBA is an array of ten radio telescopes distributed from Hawaii to St. Croix, from the Canadian border to Texas. With the VLBA, astronomers plan to look more deeply into these radio sources.

# Relativistic Jets and the Most Powerful Radio Sources in the Universe

Alan Bridle

### *Introduction*

Since the early 1950's, astronomers have known that some of the most intense features of the natural radio noise background are generated by extremely remote, powerful sources. These "radio-loud" galaxies and quasars are among the most distant objects known to astronomy. We hope that they will eventually provide us with ways to probe conditions in the universe at the time when galaxies began to form out of the matter that emerged from the "Big Bang"—the explosion that seems to have set all the visible universe in motion.

To use telescopes to study the past history of the universe, we must first understand the physics by which the matter in it radiates. Whenever we learn the physics of a class of astronomical object, we gain a chance to explore new facets of universal history by studying the furthest known members of that class. The most luminous objects in the universe are thus doubly important to us—first because explaining how they radiate so much energy is an extreme test for our physics, and second because it is these objects that our telescopes can detect at the greatest distances. Because the radiation from the most remote objects has taken longer to reach us than that from nearer ones, it brings us clues to conditions at the earliest times that we can probe by observing discrete objects. The distant, powerful radio sources are thus valuable individual "fossils" in the telescopic chronicle of the early universe.

I will first explain how consecutive improvements in our ability to make images of cosmic radio sources uncovered the properties of these remote and powerful radio transmitters. Then I will summarize the current view of their physics, and the problems associated with that view. Finally, I will suggest how this research will be advanced when the National Radio Astronomy Observatory's (NRAO) next major instrument, the Very Long Baseline Array (VLBA), is completed in the early 1990's.

### *The Radio Sky*

I will begin by introducing the radio sky. Our home is in the suburbs of a galaxy of about a hundred billion ($10^{11}$) stars, arranged in a shape like that of a lens about a hundred thousand light-years across. When we look at the night sky, we view this "lens" from a position inside it, so we see it as an encircling band of light—the "Milky Way". The first discovery in radio astronomy, made in 1933 by Karl Jansky, was that the Milky Way is a source of radio "static", or "noise". The intensity of this natural noise signal varies smoothly around the Milky Way, and is generally greatest where the visible Milky Way is brightest. The development of radio techniques during the Second World War led to a second accidental discovery when military radar operators learned that the Sun is also a strong source of radio noise.

These early discoveries of radio noise signals from the Milky Way and from the Sun implied a crude similarity between the radio sky and the visible sky. As the Milky Way is an assemblage of stars, and the Sun is the nearest star, it seemed likely that cosmic radio emissions might be energy that "trickles down" to radio wavelengths from processes in the stars of our galaxy.[1] It has turned out that there are indeed many processes by which stars contribute to the Milky Way radio emission. These processes involve most phases of the stellar life cycle from birth to death, but I will not detail them here. I want instead to focus on the next major discovery that was made by the young science of radio astronomy.

As astronomers began to explore the sky with directional receiving antennas in the late 1940's, they found that against the smooth background of radio emission from the Milky Way there are also many discrete radio sources,

[1] I say "trickled down" here both because radio photons have less energy than visible photons and because the total radio power emitted by our galaxy (about $10^{32}$ watts) is small compared with the power it emits at visible wavelengths (about $6 \times 10^{36}$ watts).

that is, localized regions of the sky that emit particularly strong radio noise. As the Sun and the Milky Way had both been detected as radio sources, astronomers first surmised that the discrete sources were also stars that are members of our galaxy. But the positions of the brightest discrete radio sources did not correspond to those of the brightest visible stars. It therefore seemed likely that the sources were produced by a previously unknown class of peculiar "radio stars". This later proved to be spectacularly incorrect, as we learned that many of the brightest discrete radio sources are associated with entire distant galaxies.[2] A conspicuous example is in the direction of the stellar constellation of Cygnus ("The Swan"), so it was called "Cygnus A". Much of this paper describes the systematic uncovering of the structure of Cygnus A, and of the physics relating to this source and to the other "radio galaxies".

### *Cygnus Revealed*

Soon after the discrete radio sources were discovered, astronomers began trying to measure their sizes. They wanted to know whether, for example, the sources were small enough to be related to individual stars. It was quickly clear that most of them were too small for their structure to be apparent when they were scanned with single radio antennas. Progress came instead when an analogy was made with optical techniques that A.A. Michelson had used in 1920 to measure the angular diameters of visible stars.

Michelson's "Stellar Interferometer" used two well-separated mirrors to collect the light from a star and then pass it through two slits to form an interference pattern. The angular size of the star could be measured by studying how the amplitude of the interference fringes varied with the separation $D$ of the mirrors. The analog in radio astronomy is to use two antennas, separated by distance $D$, to collect radio signals from a discrete source, and then to correlate the two signals. By studying how the correlated signal power varies as $D$ is varied, one can measure the angular size of the radio source. By determining the phase of the interference pattern, one can also measure the source's position in the sky.

[2] True "radio stars", i.e., stellar radio sources in our own galaxy, are generally much fainter and were not discovered until the 1960's.

When pairs of antennas were used as interferometers to study Cygnus A, the first new datum they obtained was an improved position for the center of the radio source. In 1951, this was measured accurately enough to identify Cygnus A with an optical object that was clearly not a star but an entire galaxy. Optical astronomers then found that recognizable lines in this galaxy's spectrum were displaced toward the red with a wavelength shift ($\delta\lambda/\lambda$) of 0.056. The red shift of the spectrum of a galaxy measures the velocity with which it is receding from us as the universe expands. The velocities increase with the distance of the galaxy from our own, and the velocity-distance relationship has been calibrated by measuring it for nearby galaxies whose distances can be determined in other ways. The 5.6% red shift of Cygnus A's galaxy implies that it is about 520 *million* light-years away.

Knowing both the strength of the radio signals received from Cygnus A and its distance, one can deduce that its intrinsic radio power is about $5 \times 10^{37}$ watts. For comparison, the total *radio* power emitted by the Milky Way is only about $10^{32}$ watts, and the total *optical* power emitted by its 100 billion stars is only about $6 \times 10^{36}$ watts. This sets a physical context for the radio power of Cygnus A, as the starlight in our galaxy is powered by thermonuclear fusion, a highly efficient energy source (in terms of energy release per unit mass). The enormous radio luminosity of Cygnus A relative to that of our own galaxy posed several problems. Does Cygnus A tap a much more efficient energy supply than that of fusion in its stars? Or does it contain exceptionally many stars? Or are its stars unusually efficient at channeling their energy supply into radio noise? Clearly, if the radio signal from Cygnus A is derived from processes in its stars, by analogy with that from the Milky Way, the signal should come from a region centered on, and about the same size as, the visible galaxy.

The layout of the Cygnus A radio source was first determined by an interferometer operating at 125 MHz in 1952; Figure 1 reproduces the result of this pioneering observation. Most of the radio signal comes from two extended regions, or lobes, that sit astride the galaxy. At 125 MHz, the lobes emit approximately equal powers, are about 51 arc seconds by 30 arc seconds in diameter, and their centers are about 88 arc seconds apart. Knowing the angular separation of the lobes, and the distance to Cygnus A, one can deduce that the outer parts of the lobes are 100,000 light-years outside the galaxy. The enormous radio luminosity of Cygnus A therefore comes mainly from two similar regions that are far from most of the stars (and thus from most of the *known* mass and energy resources) of the parent galaxy.

Two problems had become clear. One is of energy generation—what energy reservoir fuels the enormous radio power of a source such as Cygnus A? The other is of energy transport—how can such a galaxy funnel energy far from most of its stars, to the two "lobe" regions that emit most of the radio noise?

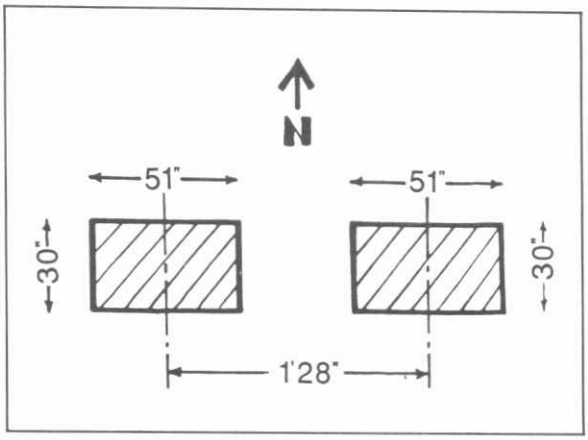


*Figure 1. The structure of the 125-MHz radio emission from Cygnus A, as determined by R.C. Jennison and M.K. Das Gupta in 1952. They found that the radio emission originates in two extended regions (depicted here as the two shaded boxes), each about 51 by 30 arcsec across and separated by about 88 arscec (1′28″). The parent galaxy is midway between the two radio emitting regions.*

### The Emission Mechanism

The observation that showed Cygnus A to be a double radio source provided other clues about the mechanism of the radio emission. Knowing the intensity of the source and the angle it subtends, one can work out its "effective brightness temperature", by asking: if the source was an ideal "black-body", how hot would its surface have to be for the observed area to emit the observed luminosity? The answer, from the 125 MHz data, is about 300 million Kelvin. A physical black-body at that temperature would be a gas that could not be restrained by the gravity of the visible galaxy. Furthermore, the intensity of the radio noise from Cygnus A (and from other sources of this class that were recognized later) increases with decreasing radio frequency (roughly as a $\nu^{-0.8}$ power law), whereas that from a black-body at 300 million Kelvin would decrease with decreasing frequency.

These results point to a nonthermal emission mechanism, that is, one in which the radio noise is emitted by matter that is not in thermal equilibrium. Of many mechanisms that have been considered, the most plausible is that the emission is synchrotron radiation: it is produced by the process that generates the intense light in the National Synchrotron Light Source at Brookhaven (though with radically different parameters in the source region). The reasoning for this is as follows. The only way to launch electromagnetic radiation is to accelerate a charge. The lightest, and therefore easiest, charges to accelerate are electrons. The only plausible way to accelerate electrons far from galaxies is for them to move in magnetic fields generated by currents in the galaxy or in the intergalactic material. To emit such an enormous luminosity from magnetic field strengths that are unlikely on energetic grounds to be more than a few tens of microgauss, the mechanism must be highly efficient. Electrons radiate most efficiently in a magnetic field when they travel at speeds close to that of light, and lose energy by the synchrotron radiation process.

Even so, the total energy reservoir required to produce the radio luminosity of Cygnus A by synchrotron radiation is startling. To calculate it uniquely, we should know the strength $B$ and geometry of the magnetic field in the source, and the luminosity $L$ and the volume $V$ of the radio emitting region. $L$ and $V$ can be inferred from the observations, but we have no prior knowledge of the magnetic field strength $B$. We can make progress despite our ignorance of this parameter, however. The total energy of the particles in a synchrotron source of luminosity $L$ and volume $V$ scales as $B^{-3/2}L$, while the energy in the fields scales as $B^2V$—for given (that is, observed) values of $L$ and $V$, the particle energy decreases, and the field energy increases, with increasing $B$. There is therefore a value of $B$ that minimizes the total (particle plus field) energy that is needed to produce the source. In this "energy-efficient" state, the total energy of a radio source would be divided about equally between the particles and the fields. We can estimate the parameters of this state for a source with known *L* and *V* by making a few plausible assumptions (for example that the large-scale fields and the particle motions are almost random—unlike those in a laboratory synchrotron, but more likely in the astrophysical context). In this minimum-energy state, Cygnus A would contain about $2 \times 10^{52}$ joules in relativistic electrons and magnetic fields, an energy budget equivalent to the entire rest mass of about 110,000 stars like the Sun. As I said above, this is a startling result, given (a) that this is a lower limit, and (b) that it must be delivered by a galaxy to regions up to a hundred thousand light years from most of its stars! At the approximately 1% efficiencies of mass-to-energy conversion in hydrogen fusion reactions in stars, about $10^7$ sun-like stars would have to contribute. But normal stars channel little of their energy output into relativistic electrons and magnetic fields, so a larger parent mass (equivalent to that of $10^8$ to $10^9$ sun-like stars) would be needed if stellar fusion reactions are the ultimate source of the energy.

This analysis raises many questions. Do these sources tap an energy supply more potent than that of thermonuclear fusion reactions? Does the stellar population of the galaxy play any role in energizing them? Can we be sure that the emission mechanism is synchrotron radiation?

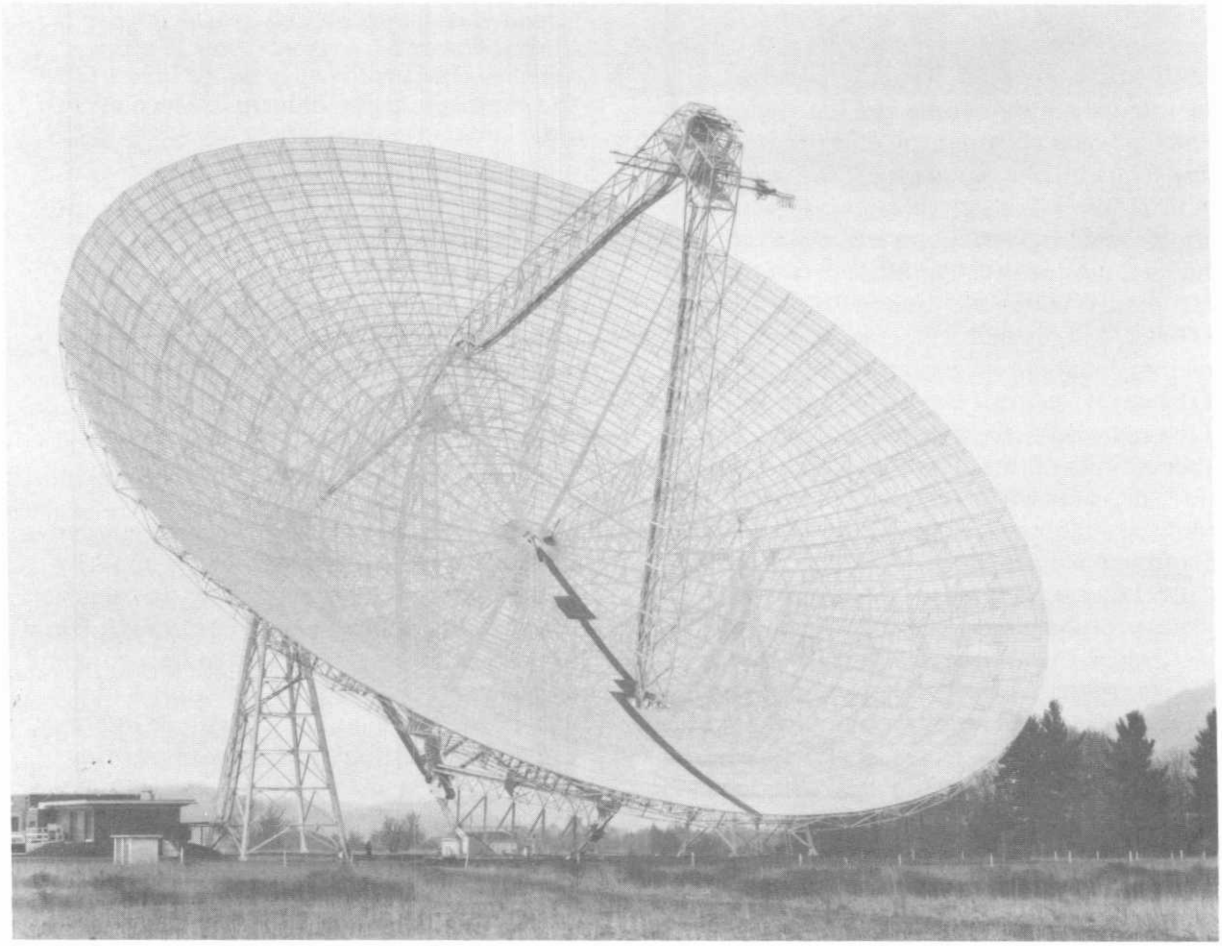

*Figure 2. The 300-foot antenna at the National Radio Astronomy Observatory in Green Bank, West Virginia is the second largest steerable radio telescope in the world. It has a paraboloidal reflecting surface with an area of 1.8 acres that focuses arriving radio waves onto receivers over 200 feet above the ground. It would clearly be absurd to extrapolate this technology to apertures many kilometers across, as required to resolve details of radio sources such as Cygnus A.*

The last question still cannot be answered with complete certainty, but the argument that I used to introduce the synchrotron mechanism here has survived close scrutiny. No one has proposed a mechanism that is both more plausible and more efficient, but the synchrotron mechanism has passed other important tests. For example, the radio emission from the double radio sources has been found to be linearly polarized, as expected if we are observing synchrotron radiation from particles that move in somewhat (but not completely) disorganized magnetic fields. Also, the minimum energy calculations for Cygnus A ask for mean magnetic field strengths about 60 microgauss; the electrons that radiate at radio frequencies would then have energies from 100 MeV to several GeV. If the electrons in Cygnus A have an energy spectrum like that observed in the primary cosmic rays at such energies, the synchrotron radiation mechanism predicts a radio spectrum similar to that observed in Cygnus A (and in other double radio sources). This agreement is comforting, though not decisive (as we are not certain where or how the cosmic ray electrons themselves are accelerated). Finally, synchrotron sources can (theoretically) reach effective temperatures near $10^{12}$K before being "overwhelmed" by inverse Compton processes; this limit is close to the maximum effective temperature that has been observed at radio wavelengths in the brightest parts of these sources. The hypothesis that radio galaxies emit mainly by the synchrotron mechanism has therefore passed every test that we can give it, while other mechanisms that have been proposed have encountered even greater difficulties.

## *Aperture Synthesis and the Radio Source Population*

The next important steps came from a technique that was developed in the late 1950's and early 1960's by Martin Ryle's group at the Cavendish Laboratory in England. To make detailed images of radio sources such as Cygnus A requires angular resolutions of a few arc seconds or better. Because radio waves have long wavelengths, a single radio antenna must have an enormous reflecting surface to provide such angular resolution. Figure 2 shows the 300-foot diameter antenna at the NRAO's facility in Green Bank, West Virginia. This is one of the largest steerable parabolic antennas ever constructed. To pick out interior details of a source like Cygnus A at centimeter wavelengths (where radio receivers are most sensitive) would require an aperture many kilometers in diameter. The technology used for the 300-foot telescope obviously cannot be extrapolated to such scales! But an extension of the interferometer principle rescues us. The information that would be brought to the focus of such a "dish" antenna is also present in the amplitudes and phases of the electric fields over the dish's parabolic reflecting surface. Ryle's group showed how to "synthesize" giant antennas by sampling the electric field's amplitude and phase over an aperture, then forming an image of the source later using a digital computer rather than by bringing the radiation to a focus via the geometry of a physical parabolic surface.

I can illustrate Ryle's "aperture synthesis" technique with Figure 3, which shows other antennas in the valley at Green Bank. As well as the 300-foot dish, there are three smaller antennas, used together as an interferometer. Relative to any one of these antennas, each of the others sweeps out a ring around it as the Earth rotates. Ryle realized that by measuring the amplitude and phase of the correlation between the signals received by pairs of such small antennas over a period of time as the earth rotates, one can reconstruct the information that would fall instantaneously on an ring-like aperture whose radius is the distance between the antennas. By moving the antennas throughout the valley in Figure 3, one can build up, over a period of many days, the information that would be collected instantaneously by an antenna almost twice the size of the valley. This technique can be used to "synthesize" huge telescopes, and has dominated high-resolution radio astronomy ever since it was first shown to be practical.[3] It is mathematically similar to measuring the hologram of the radio sky on the ground, and then reconstructing an image of

[3] It turns out that the increased time taken to gather the information by aperture synthesis is repaid in many applications, as the valley-sized antenna would instantaneously image only a narrow field of view, while the "synthesized" antenna images the wider field of view of the smaller antennas. The total time taken to image an extended patch of sky at high resolution is similar for the hypothetical valley-sized antenna and for the synthesis technique.

the sky by using a computer to Fourier-transform the hologram. It also parallels techniques that are used for crystal structure analysis by X-ray diffraction. Ryle won the Nobel Prize for Physics in 1974 for developing this method and for applying it in radio astronomy.

In the 1960's, many of the strong discrete sources were examined by aperture synthesis. Figure 4 illustrates the results from this period, displaying the intensity of the emission from Cygnus A as contours of equal noise intensity. These data confirm the basic double structure shown in Figure 1, but also hint at things to come—there are signs that the emission is more intense toward the outer parts of the two "lobes". Such studies through the 1960's showed that most of the discrete sources have two lobes astride a visible object. All the galaxies that could be identified with such wide double radio sources were massive, slowly rotating, elliptical systems containing old stars and little cool gas. In contrast, galaxies like our own Milky Way—rapid rotators, full of cool gas and young stars tracing a beautiful spiral-armed layout, never make powerful double radio sources.

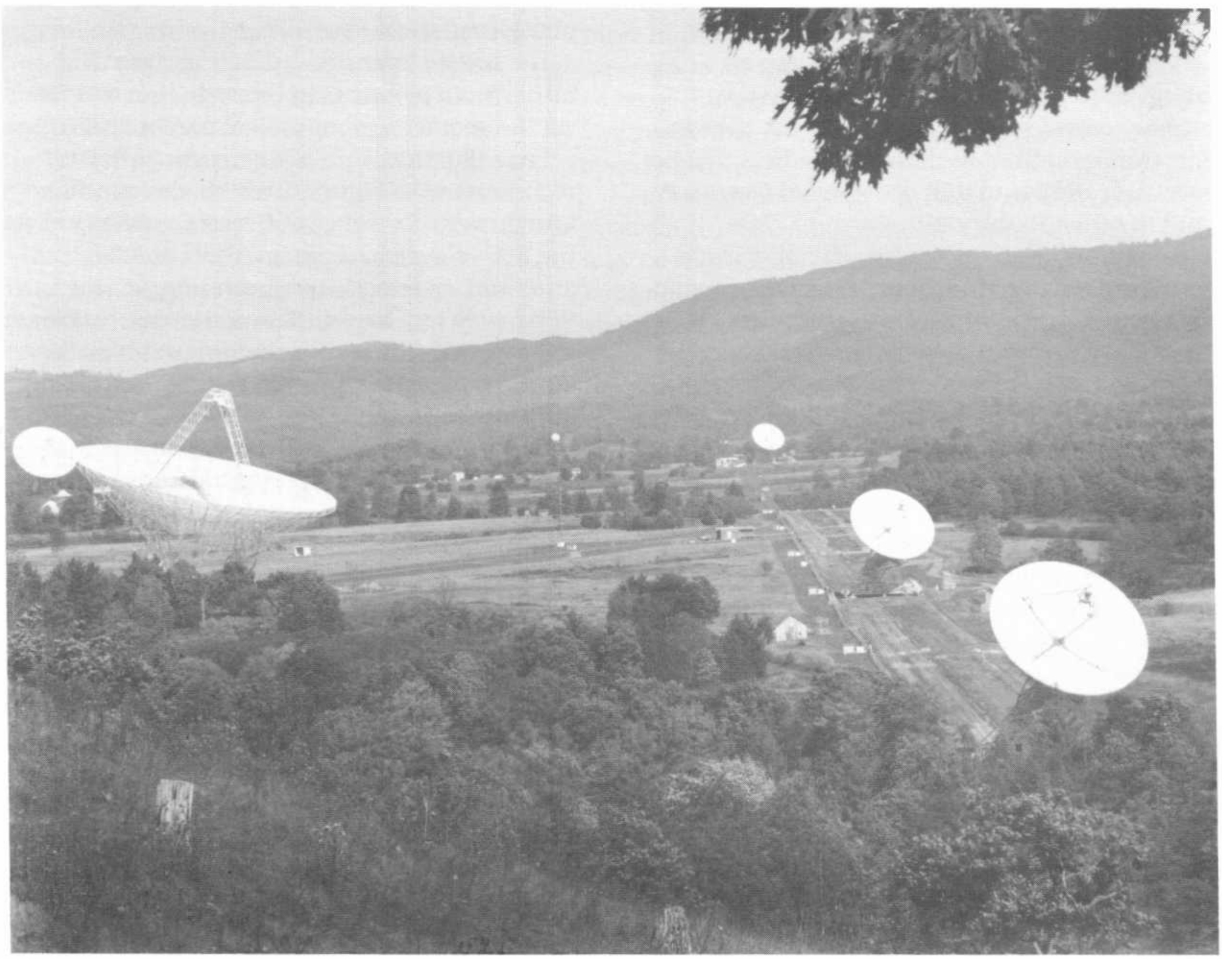

*Figure 3. General view of the Deer Creek Valley, containing the National Radio Astronomy Observatory's site at Green Bank, Virginia. The 300-foot antenna shown in Figure 2 is in the foreground to the left. The smaller (85-foot) antennas stationed in a line to the right of this view are used together as a three-element interferometer. As described in the text, these three antennas are moved both by the Earth (which rotates the whole scene around once per day) and also by relocating them along the runway that joins them, to build up the information that would be collected instantaneously by radio telescope about twice the size of the valley.*

## The Quasars

While trying to identify the visible objects associated with radio sources, astronomers took the optical spectra of some apparently star-like objects near the radio positions. These spectra remained puzzling until 1963, when it was realized that they contained red shifts $\delta\lambda/\lambda \sim 0.5$, ten times that of Cygnus A. Within a few years, red shifts up to $\delta\lambda/\lambda \sim 2$ had been found for other bright double radio sources. These red shifts imply distances up to 10 to 20 *billion* light-years (a major uncertainty being whether the expansion of the universe has been slowed significantly over such enormous times by the gravity of the matter it contains). Clearly, though, the radio waves from objects with such huge red shifts bring us information about events that occurred long before the Earth had formed! The objects became known as *quasars* (*quasi*-stell*ar* sources). We have since learned that quasars are galaxies with exceptionally luminous central regions. The great distances of the quasars associated with the brightest radio sources imply that surveys of the radio sky have now cataloged most of the extremely powerful natural radio sources in the universe. This sobering fact justifies the title of my lecture!

## The Compact Radio Sources

A few per cent of the radio sources that are identified with elliptical galaxies and quasars are not wide doubles like Cygnus A. Most of their radio emission comes instead from regions less than an arc second across, at the centers of the associated optical objects. The red shifts of these compact radio sources overlap those of the wide doubles. Most compact sources are thus not more distant (and only apparently smaller) than the wide doubles, but are intrinsically small sources with powers similar to those of the wide doubles. Some vary significantly in intensity on time scales of a year or so; this suggests that they are only about a light-year across. It was thought at first that the wide doubles might be produced by explosive events in galactic nuclei (where the mass, and thus presumably the energy supply, of the galaxy is most concentrated). Could the compact sources be an early stage in the explosive evolution of the wide doubles? This view was popular in the 1960's, but eventually foundered on a problem that I will describe

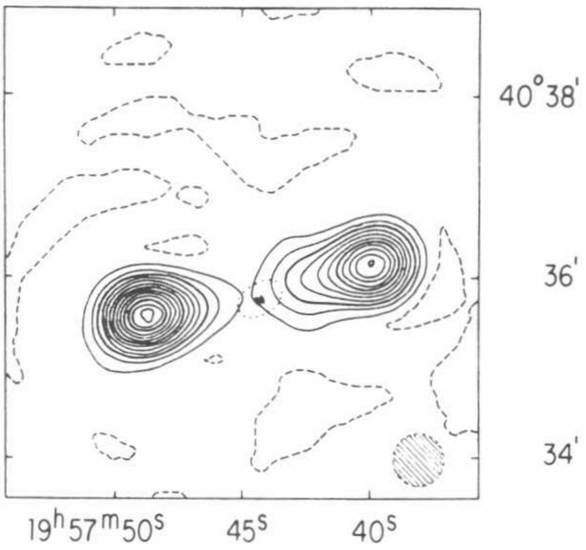


*Figure 4. The structure of the 1400-MHz radio emission from Cygnus A, as determined by M. Ryle, B. Elsmore and A.C. Neville in 1965 using the technique of aperture synthesis. The structure is shown as contours of equal radio intensity, analogous to the elevation contours on a topographic map. The hatched circle shows the effective resolution of the observations (full width to half maximum of the point spread function). The parent galaxy is illustrated by the dotted ellipse midway between the radio contours; its bright central region by the black outline at the center of this ellipse. The dotted contours trace apparently negative emission levels that result from imperfections in the radio data.*

here in some detail because it points to the origin of the present physical model for the sources.

If a radio synchrotron source was formed by an explosion in the center of a galaxy, the magnetic fields and particle densities would decrease as the source region expanded. Suppose that the source was ejected as two "plasmoids" (clouds of magnetized gas containing trapped relativistic particles) that are spheres of radius $R$, as in Figure 5. The magnetic field strength $B$ would decrease as $R^{-2}$ if magnetic flux was conserved. If the plasmoids expand adiabatically, the individual particle energies would decrease as $R^{-1}$. For a power law spectrum of particle energies (as required to explain the observed radiation spectrum) the synchrotron emission equations tell us that the luminosities of the expanding plasmoids would decrease as $R^{-5}$. If the ejected plasmoids expand

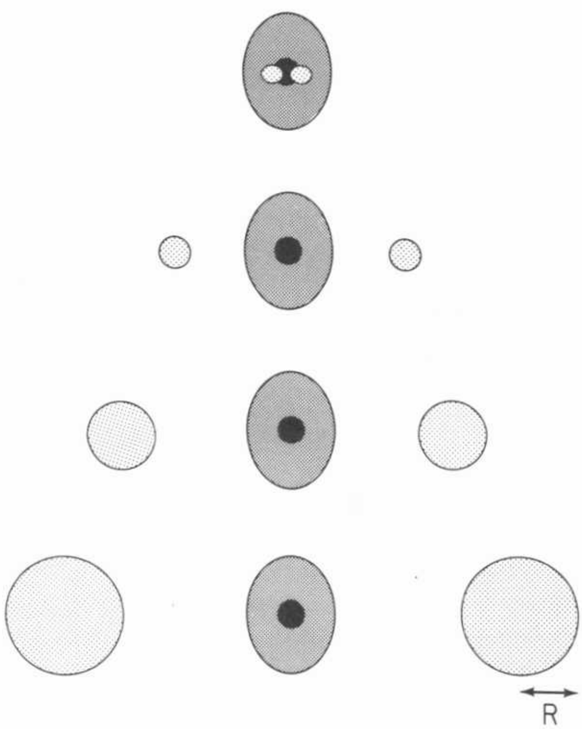


*Figure 5. Four stages in the production of a double radio source by an explosion in the center of a galaxy, as commonly envisaged during the 1960's. The stellar population of the galaxy is represented by the shaded ellipse. The black dot represents the dense central region. The lightly shaded circles represent two radio emitting "plasmoids" that break out of the galaxy along a line of least resistance to form the two emission "lobes". Attempts to relate the compact and extended radio sources along these lines were to fail, as described in the text.*

from one light-year to 100,000 light-years in diameter, the precursors of the large sources ought to be about $10^{25}$ times more luminous than the large sources themselves! Although several physical processes would intervene at small plasmoid sizes to reduce this ratio, the observed compact radio sources are evidently much too weak to be the unexpanded precursors of the wide doubles in such an "explosive" model.

### Hot Spots, Beams and Compact Cores

By the early 1970's, the relationship between the wide doubles and the compact sources was unclear, and the notion that the doubles were formed by "one-shot" ejections from their galaxies was in great difficulty. At this time, groups in Holland, Australia and the United States as well as in England were using aperture synthesis to make images of radio sources. Studies of Cygnus A (and of other wide radio doubles) continued to show important new features, as illustrated in Figure 6. There are radio "hot spots", intense small diameter features, on the outer edges of the lobes. Because these hot spots emit a high luminosity $L$ from a small volume $V$, their magnetic field strengths and energy densities in the minimum-energy state are higher than those inferred for the more extended parts of the lobes. In such higher field strengths, the radiative lifetimes of the electrons emitting at radio frequencies in Cygnus A's hot spots would be only 10,000 years, although the hot spots are 100,000 light-years from the center of the galaxy. This discrepancy means that the hot spots cannot have traveled out from the galaxy radiating as they do now, even if they had moved at the velocity of light, if their magnetic field strengths are near those that minimize the total energy. This difficulty led theorists to consider models in which there is an energy source within or near the hot spots, whose output can be converted locally into relativistic particles and magnetic fields.

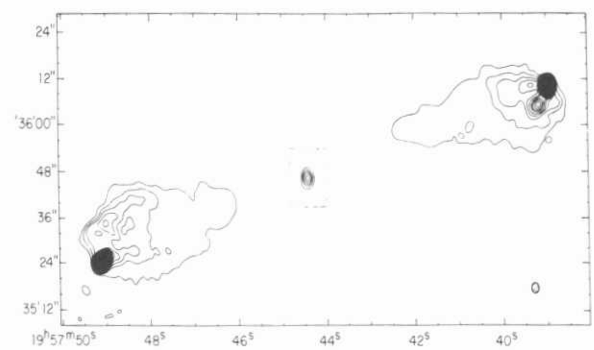


*Figure 6. The structure of the 5000-MHz radio emission from Cygnus A, as determined by P.J. Hargrave and M. Ryle in 1974 with a resolution shown by the hatched ellipse at the lower right. While fully consistent with the lower-resolution view of the source in Figure 4, this high-resolution result shows important new features. These include the "hot spots", two regions of intense radio emission marked by the blackened regions at the edges of each lobe, and the weak, compact, central component. The contour interval in the patch around the central component is one-fifth that used for the outer regions, to show this central feature more clearly.*

In 1973, a new model evolved from ideas that were originally proposed by Martin Rees in England and by Phil Morrison in the U.S.A. In this model, the extended radio lobes are presumed to be continuously resupplied with energy by a directed beam emanating from a "central engine" (of an initially unspecified nature) in the parent galaxy or quasar. The model suggested that the beam (whose composition was also unspecified at this time) could be thought of as a supersonic fluid flow. Supersonic flow was proposed for two reasons. First, supersonic flows are more likely than subsonic flows to remain stable over the required large distances. Second, matter in a supersonic flow cannot know when the "downstream" end of the flow has run into the intergalactic medium. Two oppositely-directed supersonic beams would therefore end at two shocks that travel slowly outward into the surrounding medium. Shocks can convert ordered bulk kinetic energy in a beam to other forms, including relativistic particles. They can also amplify magnetic fields. The "energy sources" for the hot spots in this picture would be the shocked ends of the beams. This model was also attractive because directed bulk kinetic energy is not degraded by adiabatic expansion. Finally, it predicted that the precursors of the wide radio doubles would be small doubles, whose luminosities should be similar to those of the wide doubles. It thus avoided the need for the over-luminous (and nonexistent) compact precursors expected by "explosive" models.

The beam model was reinforced when detailed images of many of the radio "doubles"

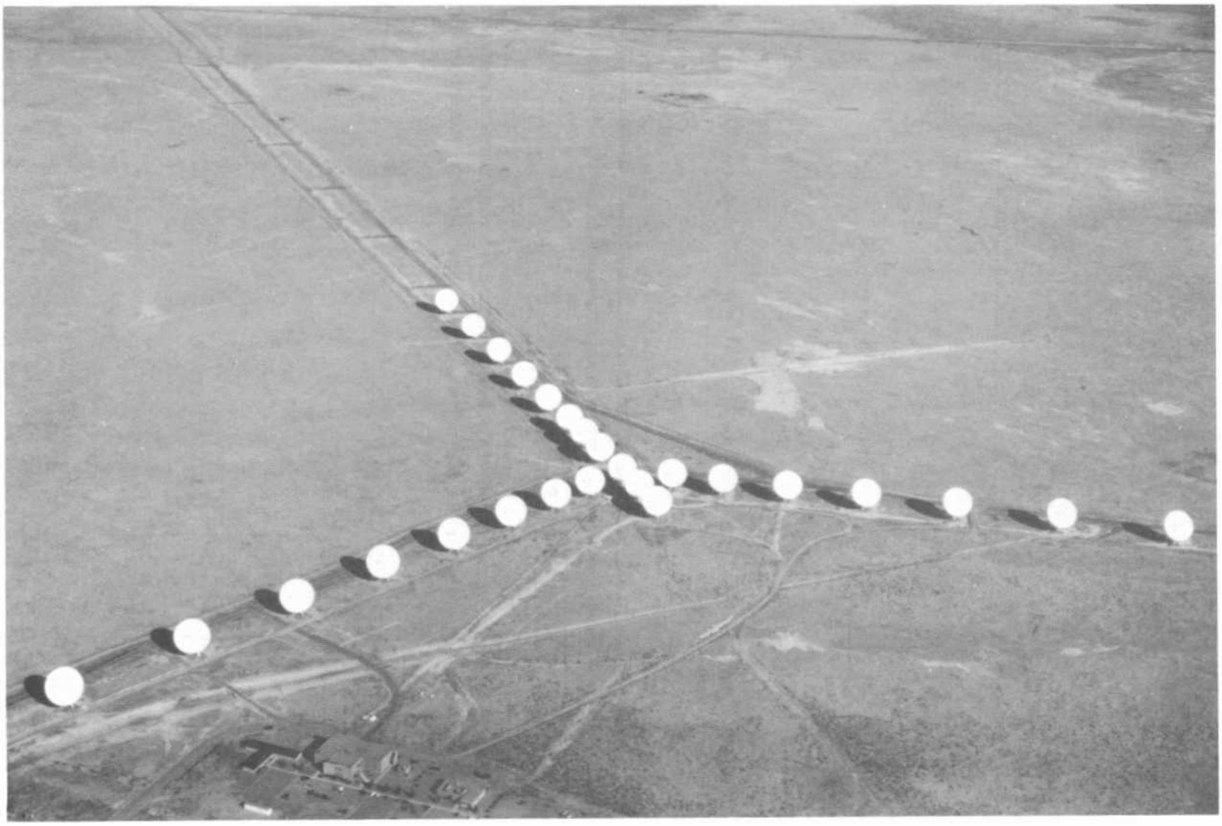

*Figure 7. Aerial view of the Very Large Array (VLA) radio telescope, operated by the National Radio Astronomy Observatory on the Plains of San Augustin in New Mexico. Twenty-six of the 27 identical 25-meter (82-foot) antennas are shown in this view, in which the antennas are in their most compact configuration. The antennas can be transported to 24 different stations along each arm of a Y-shaped railroad with two arms 21 km (13 miles) long and one arm 19 km (11.8 miles) long. In its most extended configuration, the VLA is used to image small, intense radio emission regions at high angular resolution. In the compact configuration shown here, it is used to image faint, extended regions.*

showed that they are really "triples", that is, that they often contain a compact "core" radio source in the center of the parent object, emitting typically a few per cent of the total radio power. A compact radio source with only about 0.25% of the total intensity was discovered at the center of Cygnus A, as shown in Figure 6. Such radio cores are crude evidence for ongoing activity in the parent objects. However, much more potent evidence for the beam picture followed from the next advances in radio imaging technique.

### *Radio Jets and The VLA*

Figure 7 shows the NRAO's Very Large Array, or VLA, on the Plains of San Augustin in New Mexico. This facility was built under the direction of Dave Heeschen and was fully commissioned in 1980. It is an array of 27 25-meter antennas that can be configured in four different ways along a Y-shaped railroad track whose arms are each about 20 km long. The figure shows the VLA in its most compact (and most photogenic!) configuration. To get angular resolutions from 0.1 to 1 arc seconds, (comparable to those of optical telescopes) at centimeter wavelengths, we pick these 200-ton antennas up and move them further apart. The most expanded configuration of the antennas synthesizes an aperture about the size of the Capitol Beltway around Washington, D.C. By reconfiguring the VLA, we gain the equivalent of a photographer's zoom lens—we can choose to make high resolution images of a small field of view, or lower resolution images of a much larger field.

The signals received by the VLA's 27 antennas are combined to form 351 interferometers operating simultaneously. This makes the VLA the fastest aperture synthesis instrument ever, but a more important advance has been that it also ushered in the first extensive use of digital image processing algorithms to enhance Ryle's basic technique. If we merely take the Fourier transform of the correlated signals from the 351 interferometers of the VLA, we get the view of Cygnus A shown in the top panel of Figure 8. This image has severe defects because we

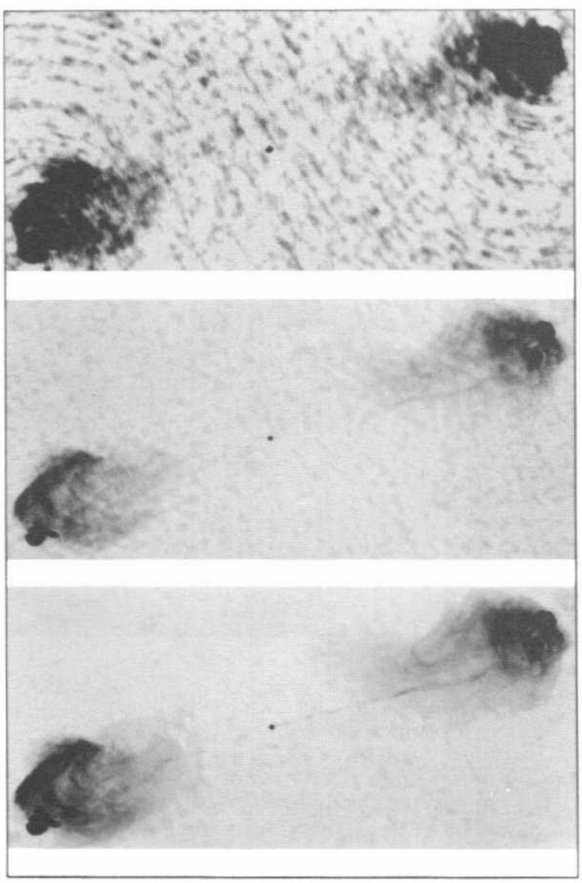

*Figure 8. Three stages in the imaging of Cygnus A with the VLA at 4885-MHz (data of R.A. Perley and J.W. Dreher). In these displays, the most intense radio emission is dark, and the least intense emission light, as in a photographic negative. The image in the top panel is severely corrupted by false responses to the emission from the bright hot spots. These responses occur because the incoming radio signals are not sampled at all possible locations in the synthesized aperture, but only on discrete "tracks" defined by the VLA's antenna stations. Because the pattern of the false responses is predictable, deconvolution from the image can produce a greatly improved display in the center panel. The bottom panel shows the further improvement obtained by using the information in the image itself to remove the corrupting effects of instabilities in the VLA electronics and of the Earth's atmosphere. The final image clearly shows the slender "radio jet" that links the central component of Cygnus A to the right-hand radio lobe.*

cannot move the antennas to every possible location on the Plains of San Augustin, but only to a finite number of stations. This finite sampling produces "aliases" of bright emission throughout the image. (These aliases are like "sidelobe" responses in a single antenna's reception pattern.) But digital image processing methods can remove these unwanted responses to image faint features near strong ones. These techniques exploit our ability to predict the pattern of the false responses accurately because the "dish surface" of the synthesized antenna is itself defined in the computer. Removing the false responses yields the second image in Figure 8. We have also learned how to remove defects in the image that are caused by instabilities in our electronics or by fluctuations in the Earth's atmosphere along the path to the source. In the late 1970's, ways were found to use the data from the image itself to estimate and correct for such effects after the signals have been correlated and recorded, that is, "off-line". These techniques are analogous to the on-line methods of adaptive optics ("rubber mirrors") in optical signal processing and in laser weaponry. The third panel of Figure 8 shows the image obtained once the imperfections introduced by these effects have been minimized. This image shows many qualitatively new features in Cygnus A, including a tell-tale thread of radio emission that links the central core source to the lobe at the upper right.

This thread is a radio-luminous "umbilical cord" where the beam modelers had proposed that there should be a continuous outflow to the lobes from the central object. An important early discovery made with the VLA was that many of the powerful double radio sources have such thread-like radio features emanating from their radio cores. Presuming that these features are indeed emission from within the outflows proposed by the theorists, astronomers termed them "radio jets". The radio jet and core in Cygnus A are both inconspicuous compared with those in many double sources associated with quasars. Figures 9 and 10 show examples of jets in wide-lobed quasars observed with the VLA. Both quasars are about 8 billion light-years from us. In both images, there is a bright radio "core" centered on the optical quasar, two extended emission lobes astride the core, and a prominent radio "jet" linking the core to one of the lobes. Such jets were rarely glimpsed in pre-VLA radio images because the image quality (resolution and dynamic range) that could be achieved using 1970's techniques and algorithms was inadequate (though enough hints had appeared before the VLA was completed making the search for radio jets one of its first research programs).

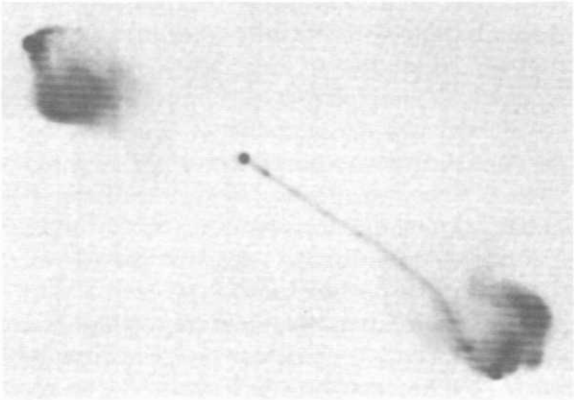

*Figure 9. VLA image of the 4885-MHz radio emission from the quasar 3C175. The parent object coincides with the bright, compact central component and has a redshift of 0.768. The radio source is over 650,000 light-years across, i.e., over six times the diameter of our own Milky Way galaxy. The radio jet is over 300,000 light-years long, and contains several internal knots of enhanced emission.*

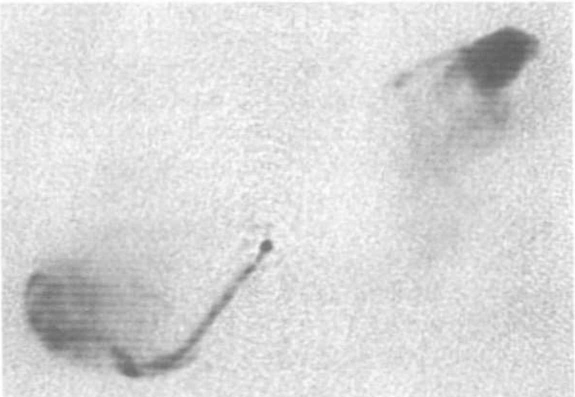

*Figure 10. VLA image of the 4885-MHz radio emission from the quasar 3C334. The parent object coincides with the bright, compact central component and has a redshift of 0.5550. The linear dimensions of the radio source are very similar to those of 3C175, shown in Figure 9. The radio jet again shows evidence of internal structure.*

Discovering thin radio features where the theorists had postulated directed energy flows began a new field of radio source research. This field hopes to explore the energy transport part of the radio source problem by relating observed features of the "radio jets" to what we know of dissipative processes in supersonic flows—either from laboratory experiments or from numerical simulations. A major difficulty is that we learn about the astrophysical flows through their synchrotron radiation, but flows that can be studied in the laboratory or modeled in computers rarely contain relativistic particles or magnetic fields. We therefore need to understand how to interpret features in flows that we see only by their synchrotron radiation. Comparisons between radio data and features of laboratory jets are difficult unless the relativistic particles and fields in the astrophysical "jets" are passengers trapped in a non-relativistic flow. Computer codes can simulate a wider range of phenomena than can be studied directly in the laboratory, but most jet modeling codes that are available to astrophysicists (and that run in reasonable times in supercomputers) either make compromises about numerical resolution or assume axisymmetry or simplistic boundary conditions.

Despite these caveats, I believe that we are beginning to glimpse the basic physics of the radio jets in the powerful sources. Many of their features resemble those of hypersonic, low density outflows whose interactions with ambient gas are mediated mainly by oblique shocks. Such shocks do not disrupt the flows, but permit them to propagate stably down pressure gradients (such as those in the atmospheres of galaxies), while their pressures oscillate above and below that of the ambient gas. Compressions of the relativistic particles and magnetic fields at such shocks enhance the synchrotron emissivity locally. The radio jets are often "knotty", as expected on this picture. Observations of the sizes and spacing of the radio knots can be used to diagnose jet flow parameters such as the Mach number. Momentum balance also implies that the shocks at the end of a low-density hypersonic jet (the "hot spots") travel into the ambient gas much more slowly than the jet flow speed. The outflow must therefore first be slowed at the terminal shocks and then be deflected into a backflow by vortices around the shock region. The backflow builds a "cocoon" around the jet, behind a stand-off bow shock. This model is a good prototype for a narrow jet feeding a wide radio lobe with a curved front, as observed in Cygnus A.

If this picture is correct, the dimensions of the backflow cocoon relative to the jet can also be used to estimate the Mach number and density of the flow. We can also estimate the energy flux in the beam (if this indeed replenishes the luminosity of the radio source) and the minimum pressures at features of the flow, such as jet knots and hot spots. When this information is assembled into a coherent model, we find that jet Mach numbers of order 10, and densities about $10^{-3}$ that of the ambient medium, are required in the most powerful sources. But the most important parameter to emerge from such analyses is an estimate of the jet flow speed; for some of the most powerful sources, such as Cygnus A, this comes out to be close to the speed of light!

This suggests that the outflows, whose composition is mostly incidental to this discussion, may be thoroughly relativistic, in the sense that not only do they contain enough trapped relativistic electrons and magnetic fields to make them visible by their synchrotron emission, but the flow itself travels out from the galaxy at a velocity close to that of light.

### *One-Sided Jets In Two-Sided Sources*

An obvious feature of Figures 9 and 10 is that each shows two radio lobes, but only one unambiguous radio jet. This is a general characteristic of the powerful sources—their jets are much brighter on one side than the other, despite the similar intensities of the main emission lobes. (The jets in less powerful double radio sources, such as that shown in Figure 11, are usually two-sided, but jet one-sidedness is systematically more obvious in sources of higher powers.) These bright asymmetries of the jets have a simple explanation if the jet velocities $v$ increase with source power, becoming close to $c$, the velocity of light, in the most powerful sources. Radiation from a jet that travels at velocity $v = \beta c$ and at an angle $\theta$ to our line of sight is Doppler shifted so that we observe a frequency $\gamma^{-1} (1 - \beta cos\theta)^{-1}$ times that which is emitted. If $v$ approaches $c$, the velocity of light, this effect significantly blue-shifts the radiation from the approaching flow, and red-shifts the radiation from the receding one. As the radio spectrum of the jets is roughly a power law increasing to the lower frequencies $\nu$ as $\nu^{-\alpha}$ the frequency shift makes the approaching flow seem brighter and the receding one fainter. The observed intensity ratio of intrinsically symmetric approaching and receding relativistic jets due to this "Doppler favoritism" is

$$\frac{I_a}{I_r} = \left(\frac{1 + \beta\cos\theta}{1 - \beta\cos\theta}\right)^{2+\alpha}$$

This can be large if $v$ approaches $c$ ($\beta \to 1$) and the jet lies close to the line of sight ($\theta \to 0$).

However, the side-to-side asymmetry might be explained in other ways. Perhaps only one outflow is active at a time (switching from side to side to build up two lobes). Or, two outflows might be present but only one has enough relativistic electrons or magnetic fields to be detected as a synchrotron source. There are other observations, however, that suggest that some parts of the radio jets move at speeds close to that of light.

### *Breaking The "Speed Limit"*

For radio astronomers to image the internal structures of the compact sources, and of the central radio cores in wide doubles, we need arc-millisecond resolution—meaning telescopes that are effectively thousands of kilometers across. When synthesizing apertures on the scale of the VLA, we bring the signals about 20 km from the individual antennas to a correlator over waveguide paths in real time. To span thousand-kilometer scales, we record the signals at the separated antennas and play them back later in exact synchronism at a central correlator. The path from the antenna to the correlator is a reel of digital tape in a truck, instead of thousands of kilometers of waveguide or optical fibers! This technique, of Very-Long-Baseline Interferometry (VLBI), was pioneered in the U.S.A. and Canada in the late 1960's. It has been used to integrate antennas all over the world into a single planet-sized radio telescope. So far, the method has been practical only for a few special experiments per year, but it has been used to image the inner few arc-milliseconds of some strong sources, with one especially dramatic result.

It was learned in the 1960's that the intensities of some of the compact radio sources vary significantly on time scales of years, or even faster. Imaging with arc-millisecond resolution showed (a) that they contain miniatures of the large-scale one-sided jets and (b) that their structures vary. Figure 12 illustrates this result with an image of the radio emission from near the center of a quasar, 3C273. The structure contains a still-unresolved core and some more extended features that resemble knots in a one-sided jet. These features have clearly separated from the core over a period of about three years. This is obviously reasonable if the features are at the base of an outflow from the core. They may be regions where the outflow is denser than normal, such as outward-moving shocks. But if one turns the measured angular velocity of this motion into a linear velocity, knowing the distance to the source via its red shift, that velocity is apparently 5.3 times the speed of light!

*Figure 11. VLA image of the 1465-MHz radio emission from a radio galaxy at about the same distance from us as Cygnus A, but whose radio power output is less than a thousandth that of Cygnus A. This radio source is about a million light-years across. In this weak source, radio jets are detected on both sides of the parent galaxy. The parent object is a member of a cluster of galaxies, some of whose other members also contribute to this wide-field radio image. In this source, the radio jets appear to have been bent backwards as a result of the galaxy's motion through the tenuous atmosphere of the cluster. The jets in such weak sources are probably low-velocity analogs of the relativistic jets in the most powerful sources.*

Because the outward velocity is apparently faster than that of light, this phenomenon has been called "superluminal motion". Such apparent motion does not imply new physics that defies the speed limit prescribed by Einstein's theory of relativity. Rather, it is something that we should expect to see when a relativistically-moving flow points almost at us, as Figure 13 demonstrates. Suppose that a flow contains features, such as blobs of plasma or shocks, that move with a velocity $\upsilon$ at an angle $\theta$ to the line of sight. The emitting features move from position 1 to position 2 in a time interval $\delta t_e$; they travel a distance $\upsilon\delta t_e$ along the jet path in this time. But the observer sees only the transverse component $\delta\ell = \upsilon\delta t_e \sin\theta$ of the motion, and also receives the radiation at times separated by $\delta t_o = \delta t_e (1 - \beta\cos\theta)$. The observer therefore computes an apparent transverse velocity of

$$\upsilon_{app} = \frac{\delta\ell}{\delta t_o} = \frac{\upsilon \sin\theta}{1 - \beta\cos\theta}$$

Time delays and geometry can therefore make $\upsilon_{app} >> c$ if $\upsilon \rightarrow c$ and $\theta$ is appropriate. For a jet with a bulk Lorentz factor $\gamma = (1 - \beta^2)^{-1/2}$, apparent velocities $\upsilon_{app} \sim \gamma\upsilon$ will be observed at angles $\theta \sim \gamma^{-1}$ radians to the line of sight. The apparent superluminal motion in 3C273 could therefore be explained if the observed features are moving with a Lorentz factor $\gamma \sim 5$ at about 10° from our line of sight. It is reasonable that a few percent of all sources in a randomly-oriented sample would have their jets so close to the line of sight. Only the approaching jet is seen, because of "Doppler favoritism".

These ideas lead to the relation between the compact and the extended sources that is sketched in Figure 14. We suppose that the powerful sources contain roughly symmetric outflows with velocities close to that of light, feeding two radio lobes. If we look at right angles to the radio structure we see two lobes, and nothing exciting in the center. If we look at an oblique angle, our view of the lobes is not altered radically (the structure of the source may become confused because the lobes are partly superposed on one another), but the Doppler favoritism makes the emission from the jets appear one-sided. If the jets are oriented sufficiently close to the line of sight, the Doppler boost may produce a source that

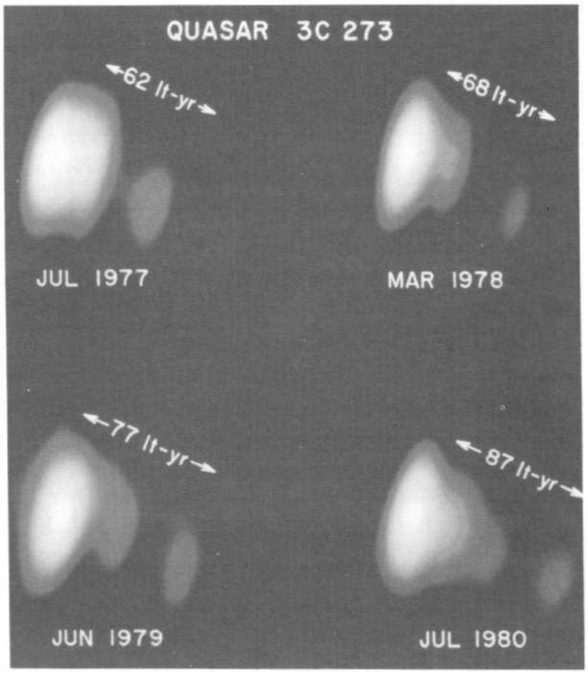


*Figure 12. Images of the central region of the quasar 3C273 with arc-millisecond resolution at 10650 MHz, obtained by T.J. Pearson, S.C. Unwin, M.H. Cohen, R.P. Linfield, A.C.S. Readhead, G.A. Seielstad, R.S. Simon and R.C. Walker in 1981 using Very Long Baseline Interferometry (VLBI) to link five antennas from West Germany to California. The images document the internal motions of knots in the source over a three-year period, showing an expansion at a velocity that is apparently faster than that of light.*

appears to be dominated by a central compact component, in which we may find superluminal motions with VLBI techniques. It is therefore attractive to interpret the small fraction of core-dominated compact sources as those whose jet flows happen to be favorably aligned with respect to us.

Several other observations reinforce this view. Where one-sided jets are detected on both the parsec (generally arc-millisecond) and kiloparsec (generally arc-second) scales in the same object, the larger-scale jet is a plausible continuation of the small scale one, on the same side of the unresolved core. It is therefore likely that jet one-sidedness has a common origin on both scales, as provided for by the relativistic jet hypothesis. The small-scale jets are also well aligned with the large scale jets in sources with weak cores, but significantly misaligned with them in sources with strong cores. This can be understood if most jets are slightly bent, as viewing a small bend almost "head-on" projects it into an apparently much larger one. Most large-scale jets do indeed appear to be slightly bent, in agreement with this notion.

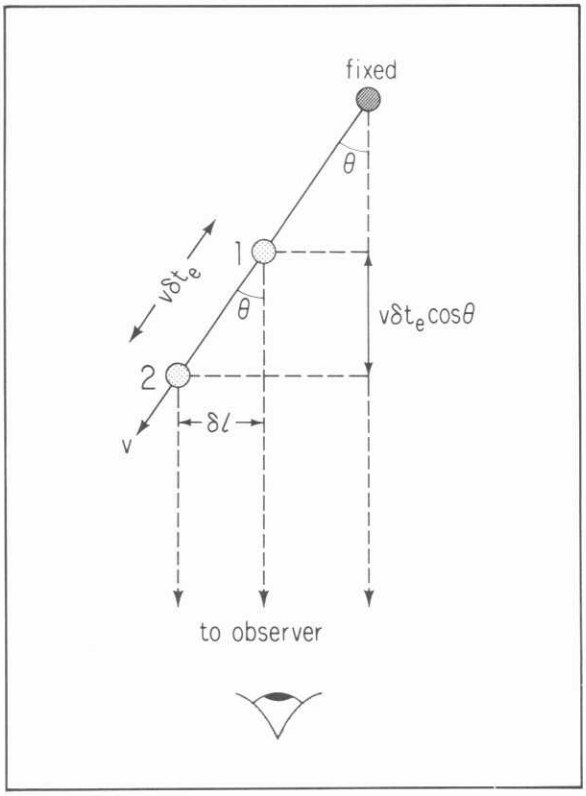


*Figure 13. A diagram showing how motion of features along a jet can apparently break the speed limit set by the velocity of light. The dark circle represents a fixed feature, the lighter circle a second feature that moves from position 1 to position 2 at velocity v in a time $\delta t_e$. The observer is far away in a direction that makes an angle θ to the motion of the traveling feature. As explained in the text, this geometry can lead to apparently faster-than-light growth of the projected separation $\delta l$.*

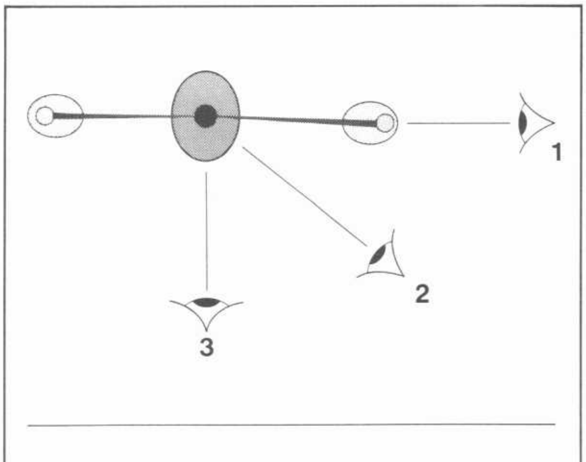


*Figure 14. The modern paradigm for the relationship between compact and extended sources. The upper panel shows two radio jets emanating from the central region (dark circle) of galaxy or quasar (dark ellipse). The jets (shaded cones) terminate at hot spots (circles) and their backflow forms the radio lobes (lightly shaded ellipses). If the jets are relativistic, the appearance of the source depends strongly on its orientation relative to the observer. The views obtained by three different radio observers are sketched in the lower panel, where dark features represent apparently intense radio emission, and light features apparently faint emission. Observer 1, almost aligned with jets, sees the central region and the approaching jet strongly amplified by Doppler boosting, but records the other features at about the correct intensity. Because this observer's line of sight is close to the jet axis, the true layout of the source is obscured by projection effects. Observer 2, at an oblique angle to the source axis, sees the source foreshortened, but may detect only one jet, due to "Doppler favoritism". Observer 3, almost perpendicular to the source axis, sees the source laid out correctly, but both of the jets and the central radio component may seem unduly faint because their radio emission is partly beamed away from the line of sight by the bulk relativistic motion.*

### *Nature of the "Central Engine"*

To complete the picture of the powerful sources, we must ask how flows may be launched from the center of a galaxy or quasar at velocities close to that of light. The hypothetical "central engine" must be able to liberate a total energy equivalent to the rest mass of $10^5$ stars like the Sun at rates up to $10^{38}$ watts, that is, about $2 \times 10^{-2}$ solar rest-masses per year, in the most powerful sources. It must do this in the form of a jet that is well collimated a few light-years away from the "engine" (to explain the jet-like features seen by VLBI). The "engines" must have sizes less than a few light-years (the typical distance between individual stars in our part of the Milky Way!) A few compact sources vary significantly on time scales of days at optical and X-ray wavelengths, so even smaller (light-day) scales may be relevant.

Relativistic jets are most likely to originate from interactions in a relativistically deep potential well, that is, in the gravity-dominated environment of a mass so compact that the full equations of General Relativity are required to describe it. Everything that we know about the "central engine" suggests that it indeed contains a large mass in a small volume. General Relativity tells us that the ultimate fate of large masses in small volumes is for gravity to dominate all other forces, forming "Black Holes". The Black Hole is a mass with a gravitational potential well so deep that not even photons can climb out of it; the "escape velocity" exceeds that of light. This terminology emphasizes the conditions within the so-called Schwarzschild radius of the center of the mass, but the most interesting region for the physics of radio source "central engines" is just outside this radius. Here, matter can stably orbit in the Black Hole's gravitational field, while energetic processes occur whose consequences can reach the outside world. The generic model for the central engine is thus a "Black Hole Plus".

### *The "Black Hole Plus"*

The interactions between gas and stars in galaxies allow a fraction of the contents of a galaxy to lose energy and to settle toward the galactic center with small, but finite, angular momentum. The most likely final configuration of the settled material is a centrifugally flattened disk around a rotating central mass. The angular momentum of the material is ultimately stored as rotation of the central mass and as orbital motion in the surrounding disk. The disk is supported centrifugally in its equatorial plane and vertically by whatever pressures are generated within it.

Orbital dynamics near a Black Hole contain some peculiarly relativistic effects. The effective potential for radial motion at a given angular momentum differs from the simple Newtonian potential in having a relativistic "pit" at its center. Material with low (but not zero) angular momentum has no stable orbit and must spiral into the hole. However, there is a range of distances and angular momenta in which stable circular orbits are possible. Most of the material in the disk has parameters within this range, but the system is dynamic. Viscous interactions generate torques that transfer energy and angular momentum outward in the disk. The material with the lowest angular momentum drifts to the center and is added to the rotating Black Hole, whose spin energy can be up to 29% of its mass energy.

If matter continues to rain down onto the system, the mass of the Black Hole increases as it acquires low-angular momentum material from the disk. The detailed structure of such a "Black Hole Plus" system is controlled by several parameters. One is the mass arrival (accretion) rate relative to a critical value known as the Eddington rate, which determines the dynamical importance of radiation pressure in the system. If accretion "smothers" the system, radiation is trapped and contributes to the vertical support of the disk. The second is the inflow time scale (set by viscosity in the disk) and its ratio to the cooling time scale. This combination controls the temperature of the gas. If the in-falling gas cannot cool effectively, the inner parts of the disk will be thick, supported either by radiation pressure (at high accretion rates) or by gas pressure (at lower accretion rates).

### *Launch Mechanisms For Relativistic Jets*

Most of the recent models for the "central engine" rely on highly efficient energy releases that are possible as material accretes onto a "Black Hole Plus". In principle, up to 42% of the total rest energy of the infalling material can be made available, as this is the fraction of the rest energy that has been liberated from gravitational potential energy at the last stable orbit around a rotating Black Hole. Although not all this energy can be extracted to "infinity", several mechanisms have been suggested whereby some material can get more than its fair share of the free energy and then escape preferentially at right angles to the disk.

Some models rely on the existence and the geometry of a "funnel" over the rotational poles of the Black Hole. The "funnel" is a region around the rotation axis within which material must either have positive total energy, and thus escape, or have so little angular momentum that it falls into the Black Hole. On the funnel walls, the angular momentum per unit mass equals the critical value. The evacuated funnel provides two ready-made channels leading to the outside world. For example, if the disk is supported primarily by radiation pressure, a radiatively driven "wind" should leak out of the funnel. Such winds can have speeds corresponding to Lorentz factors $\gamma$ up to about 2, but this is not enough to explain the superluminal motions observed within some compact sources. There is also doubt about the stability of thick disks to azimuthal perturbations.

More exotic acceleration mechanisms involving electromagnetic or magnetohydrodynamic effects in the disks seem more likely to reach bulk Lorentz factors as high as those implied by the fastest superluminal motions. These mechanisms generally suggest that an external current system creates a large scale magnetic field that threads the rotating disk. The disk will be fully ionized and thus a good conductor. The threaded fields are therefore wound into a toroidal configuration by the rotation of the disk until this winding generates large electric fields. Various calculations have shown that electrodynamic processes could then launch a Poynting flux jet up the rotation axis of the disk. Charges may also be stripped from the disk and be accelerated along the magnetic field lines, creating a centrifugally driven magnetohydrodynamic wind. It appears possible, at least in principle, for such effects to extract large powers from a spinning Black Hole embedded in a dense magnetized disk, provided the power escapes preferentially up the rotation axis without disrupting the disk.

### *The State of the Models*

Although many details remain to be worked out, such "Black Hole Plus" models hold great promise for making relativistic jets as an integral part of the process of accretion of gas and stars from throughout a galaxy onto its nuclear region. The "fuel" for the "central engine" would then be gas and stars that settle toward the center of the galaxy.

In some models, the fundamental energy supply of the radio sources is the gravitational potential energy released from this in-falling matter. In some electromagnetic models, the gas acts as a catalyst rather than directly providing the energy; in others, the rotational energy of the central Black Hole is extracted by magnetic braking. But if the "engine" is "started" by gas that falls to the center of the galaxy, we may be able to understand why the spiral galaxies do not make powerful radio sources. Although spiral galaxies may have small Black Holes at their centers, their gas and stars are centrifugally supported—their huge flattened disks, like the "lens" of the Milky Way, are stabilized by rotation with a relatively large angular momentum per unit mass. In contrast, the elliptical galaxies are not rotationally supported or highly flattened. Parts of the "central engine" may therefore exist in both types of galaxy, but in spirals such as our own galaxy its fuel supply is restricted by the general rotation.

The "combustion chamber" is likely to be the environment of a Black Hole of about $10^8$ to $10^9$ solar masses, whether the energy that is extracted is rotational or gravitational in origin. In either case, the efficiency (energy released per unit rest mass) can be as high as 10% or 20%, much higher than that from nuclear fusion. Furthermore, mechanisms exist for coupling this effectively to a "transmission" that is an electro or magnetohydrodynamically launched jet with a bulk Lorentz factor $\gamma$ as high as 5, a few light-years away from the Black Hole. The fluctuations at the base of the jet that let us observe the superluminal motions may be related to instabilities in the disk, or to fluctuations in the mass accretion onto it.

Little of this basic picture can be verified directly. The smallest region we can resolve by VLBI in a nearby source is about $10^{14}$km across, while the Schwarzschild radius is about $10^8$km times the mass of the Black Hole in units of $10^8$

solar masses! The "Black Hole Plus" physics also deals with high energy interactions in strong gravitational fields, where we cannot test General Relativity directly. Computer simulations also play an important role in modeling the stability and structure of the disks and in solving the equations of electro and magnetohydrodynamic models for the energy release. The validity of the models is thus tied to the validity of these simulations. There are, however, some troublesome observations that I have left until the end to discuss because it is just these problems that the VLBA, the NRAO's next major instrument, will be able to attack.

### *VLBA for the 1990's*

Figure 15 illustrates the VLBA, which will be the NRAO's new instrument for the early 1990's. It will be an array of 10 radio telescopes distributed from the Caribbean to Hawaii, with a concentration around the VLA in New Mexico. (For some experiments, the VLA and the VLBA may eventually be linked to image wide fields of view with the angular resolution of a planet-sized telescope). The VLBA will differ in several crucial respects from the arrays of existing antennas that produced the initial evidence for superluminal motions. These arrays are put together by coordinating observations at many different institutions, and scheduling their antennas to look at the same object simultaneously. The antennas have been built for other purposes, differ in their electromechanical properties, and so are difficult to use together effectively, especially for observations of polarized emission that will give clues to magnetic field structures in the compact sources. The arrays are also not available for full-time VLBI use. The VLBA will be a dedicated planet-sized telescope with identical antennas in full time use. It will give good

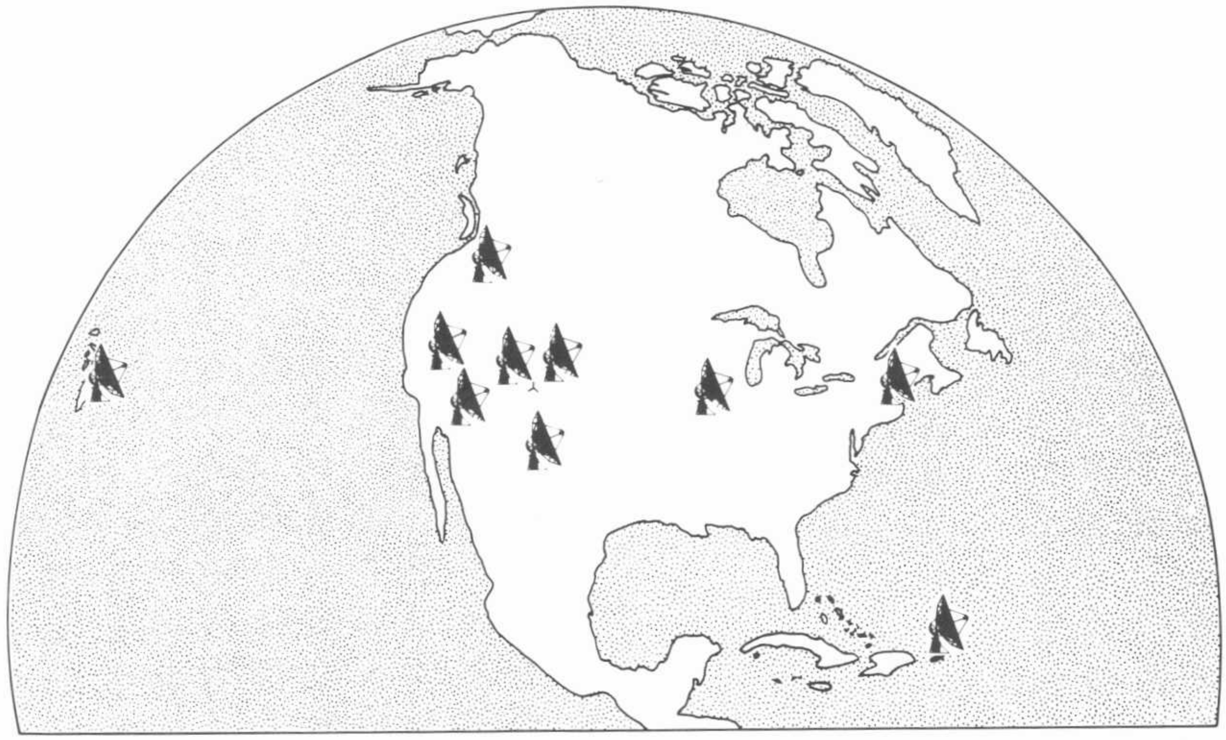

*Figure 15. Schematic of the Very Long Baseline Array (VLBA), now being constructed by the National Radio Astronomy Observatory. This radio telescope will be made up of ten automated 25-meter (82-foot) antennas distributed from Hawaii to St. Croix. Each antenna will independently record the data it receives during coordinated observations of a target radio source. The magnetic tapes from each antenna will be sent to New Mexico and correlated there in a specially designed digital computer capable of nearly one trillion multiplications per second. Subsequent processing of the correlated data will allow the synthesis of an aperture 8000 miles in diameter, making the VLBA the largest dedicated radio telescope on Earth.*

image quality because it has been designed to take full advantage of the advanced image processing concepts that have transformed the images from the VLA. The example of Cygnus A shows us that although crude images revealed basic physical problems, such as the size and double structure of radio galaxies, important clues to the solutions (such as hot spots and jets) were hidden until the image quality improved. May we now be misinterpreting the superluminal motion because we have only relatively crude pictures of it?

A major problem at present is that too many sources appear to exhibit superluminal motions. If the relativistic jet picture is correct, superluminal motion requires the jet to be oriented near the line of sight, so only a few sources in a randomly oriented sample should show it. Most of the sources that can be studied with present VLBI arrays have bright, compact cores. They may therefore form an orientationally biased sample (due to brightness boosting by the Doppler favoritism), in which superluminal motion is more common than it would be in a randomly-selected one. The VLBA will allow us to explore how the apparent velocities of features in the cores correlate with independent indicators of the orientation of the sources in larger, and perhaps less biased, samples. We will also be able to study the "superluminally moving" radio blobs to learn whether their kinematics, brightness evolution, and magnetic properties are consistent with interpreting them as features of relativistically moving flows. The VLBA will undoubtedly make its first contributions to the physics of powerful radio sources in these areas.

Radio astronomers have been trying to understand the physics of the most powerful sources for over 40 years. Each new improvement in our imaging ability has led to new physical insights, as I hope this lecture has demonstrated. The VLA convinced us that "beam" models are appropriate for the whole population of such sources. Testing whether the radio jets are fully relativistic will be a major step toward understanding how they are launched, and thus toward understanding the nature of the central engines. Only when we understand both the central engines and how they are fuelled will we know the place of the powerful radio sources in the evolution of galaxies, and thus in the evolution of the universe as a whole. Studies of radio jets with the VLBA will take us closer to the heart of these problems than ever before.