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VLBI

A New Frontier in Astronomy

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The contributions of radio astronomy to our knowledge of the universe have been impressive. They include the discoveries of quasars and radio galaxies, the largest and most powerful objects known; the discovery of the microwave background radiation, now widely accepted as confirming the Big Bang theory of the origin of the universe; and the discovery of pulsars, which provided impetus to studies of ultra-dense states of matter and collapsed objects. Without exception, these discoveries have been the result of technological innovations. *We are now witnessing a new technological breakthrough, in which Caltech is playing a leading role, which enables us to make images of objects only a few light years in size in the nuclei of the most distant galaxies and quasars.* The present methods and images are crude, but the full potential of these developments will be realized by means of a properly designed very long baseline interferometry (VLBI) telescope.

Galileo constructed the first astronomical telescope in 1609. His observations showed that a telescope performs two major functions:

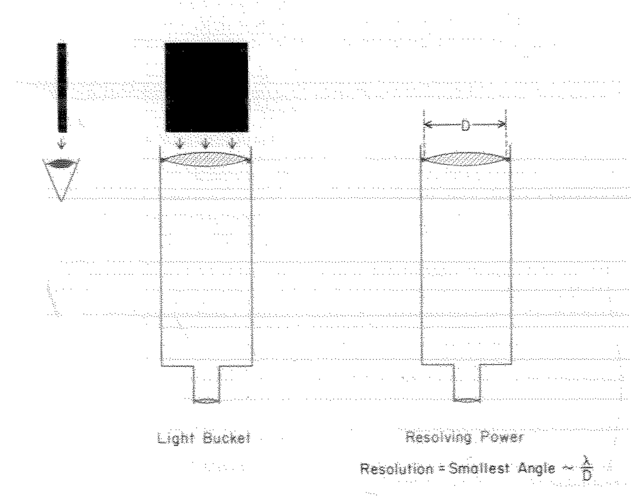
1) It is a light bucket, collecting more light than the naked eye and enabling us to see fainter objects.

2) It brings together light from points that are farther apart than the diameter of a pupil, and this enables us to see greater detail in the object.

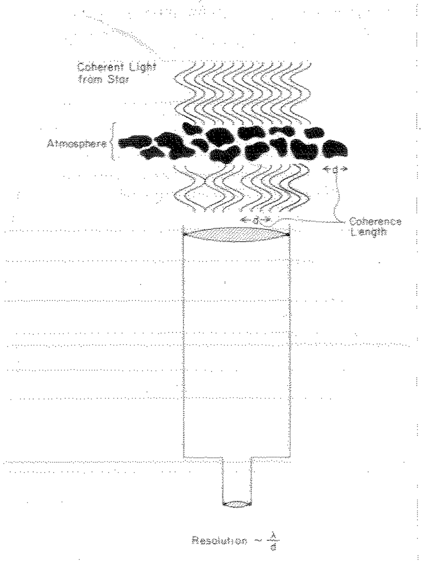
The second property is called the resolving power, or resolution, of a telescope. The resolution is given by λ/D, where λ is the wavelength of the radiation and D is the diameter of the telescope aperture. In order to see fine details in astronomical objects, we need to make D large and λ small.

Unfortunately the story is not quite this simple because the atmosphere interferes with the light on the way to the telescope. This is the same phenomenon that causes the twinkling of stars. When we look at a star with a large telescope, the light entering the telescope is not all in step, that is, it is not coherent. This corrupts the image, and the resolution we get is limited by the size of the refractive cells in the atmosphere — typically a few inches. The corresponding resolution is about one second of arc, which is not much better than the resolution Galileo achieved with his telescope. Thus, in one step Galileo achieved about the maximum resolution possible from the surface of the earth in visible light.

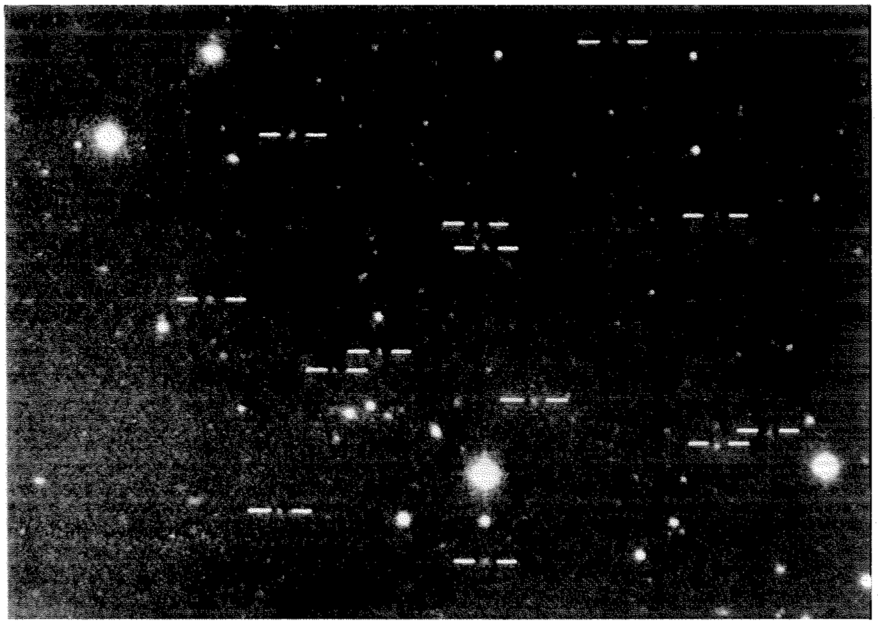
For 350 years this situation was unchanged. This meant that in the most distant galaxies, which are about 10 billion light years away, any details on a scale smaller than about 50 thousand light years — that is, roughly the size of a galaxy — were unresolved. At first sight the limited



Since a telescope collects more light than the naked eye, it enables us to see fainter objects; it also collects light from points farther apart than the diameter of the eye, allowing greater perception of detail. The resolution of a telescope is given by the wavelength (λ) of the light divided by the diameter of the aperture.



The resolving power of a telescope is limited by the size of the refractive cells in the atmosphere. Coherent light from a source is put out of step by these cells, whose size is typically a few inches, with the result that coherent signals are also only a few inches across regardless of the size of the telescope.



Galaxies more than a billion light years away (in brackets) are barely visible as unresolved blotches in this image from the 200-inch Hale Telescope. Because their resolution is limited by the atmosphere, optical telescopes cannot discern details smaller than 50 thousand light years at these distances. With very long baseline interferometry astronomers can now see details only a few light years in size — approximately the distance between individual stars in objects at these immense distances.

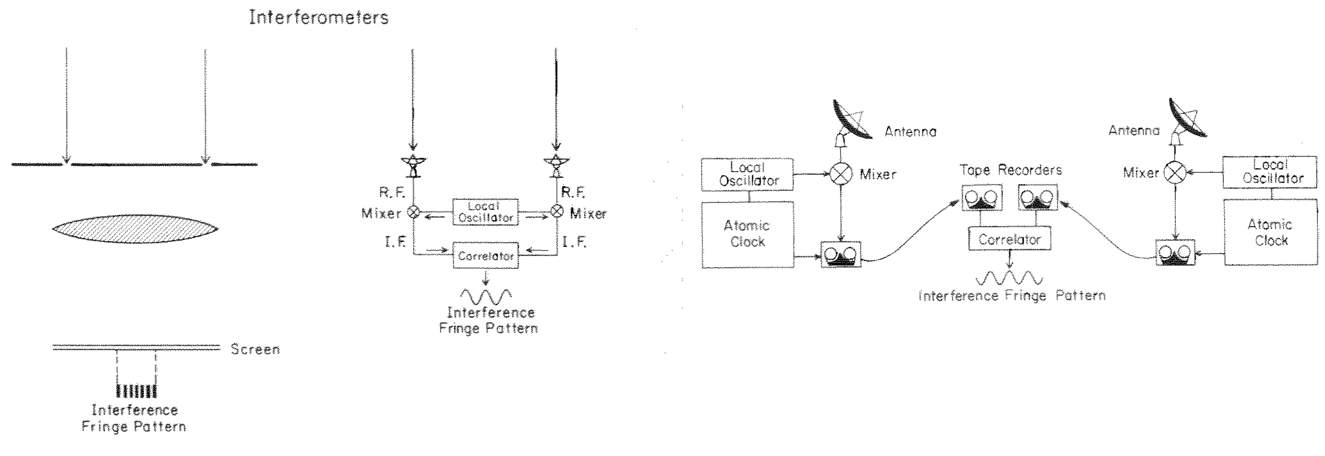
resolution of optical observations may not seem important. After all, there are plenty of nearby galaxies that can be studied in detail, so why bother about the more distant ones?

One answer is that in looking to great distances one is looking backwards in time and may therefore hope to unravel the story of the evolution of galaxies. But as we shall see, there is also another powerful incentive, which was initiated not by optical but by radio astronomical observations. By the early 1950s hundreds of celestial objects that emitted radio waves had been detected. They were thought to be stars in our own galaxy. Then, in 1953, Baade and Minkowski identified the optical counterpart of one of the strongest of these radio emitters, Cygnus A, as a distant galaxy (1 billion light years away). This was an astonishing discovery — if one of the brightest radio sources was actually a very distant galaxy, then the fainter radio sources are probably even more distant objects that might even be invisible on optical photographs. The discovery was also remarkable because it indicated that the total energy associated with the radio emission alone is 10^{61} ergs — equivalent to the yield obtained from the thermonuclear burning of a billion suns.

By the early 1960s it was known that there are essentially two types of radio objects: extended objects like Cygnus A and a class of compact objects that coincided with star-like optical objects. These were called quasi-stellar radio sources or quasars. In 1963 Caltech astronomer Maarten Schmidt interpreted the spectrum of one of these objects (3C 273) and showed that it was at a very great distance indeed — about 2.5 billion light years. This meant that 3C 273 is intrinsically 100 times brighter than the brightest galaxy.

There is no way to observe the structure of quasars with ground-based optical telescopes. However, the small scale atmospheric irregularities that limit optical resolution do not affect radio observations. Thus, it was thought, it might be possible to observe the structure of these objects with radio telescopes. This was bound to be difficult because even short radio waves are about 50 thousand times longer than light, so we would have to build a radio telescope much larger than optical telescopes to get reasonable resolution. To achieve a resolution of one arc second we would need a radio telescope five kilometers across. Of course, we cannot build a single telescope five kilometers across, but *it is possible to use interferometers to synthesize, or fill in, large telescope apertures.*

An interferometer is an instrument in which we add together light or radio waves from two points. A radio interferometer is an exact analog of an optical interferometer. In a radio interferometer the signals from the two telescopes have to be synchronized to within a fraction of a microsecond before being added together. This is usually achieved by making the connecting cables from the two telescopes equal in length. *In order to use an interferometer to synthesize a large telescope, we have to measure*



An optical interferometer (left) and a radio interferometer work on similar principles; the interferometer adds the signals from two telescopes together. Waves from the two telescopes that are in step produce constructive interference resulting in a bright region on a fringe pattern. Destructive interference, where the crests and troughs are opposite and cancel each other out, produces a dark region. The intensity of the gradations from bright to dark can be plotted as a sine wave, whose amplitude and position can be used to give an image of the signal's source. The relative positions of the interferometer elements can be changed so that the signals from each position fill in a piece of an aperture with a diameter much larger than that of a single telescope. Apertures up to thousands of kilometers can be synthesized (above) since the invention of atomic clocks, which make it possible to record and synchronize the signals with micro-second accuracy. So the signals can be added together at any location, freeing the two telescopes from the necessity of being connected.

both the size (amplitude) and the position (phase) of the sinusoidal output of the interferometer. For example, if we have a radio interferometer consisting of two radio telescopes linked by equal cables, we can make measurements with the telescopes in different relative positions and so fill in, or synthesize, an aperture that is much larger than the individual telescope. A variation on this theme makes use of the rotation of the earth to change the relative positions of the telescopes as seen from a distant celestial object. This technique was developed by Sir Martin Ryle and his colleagues at Cambridge, England. It has also been used successfully here at Caltech, in Holland, and at the Very Large Array (VLA), a group of 27 radio telescopes recently completed in New Mexico.

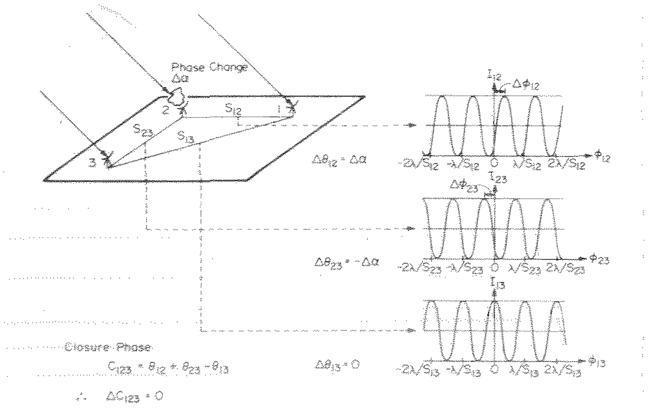
Early radio interferometry revealed some surprising images of radio objects; it showed that emission originates in two main regions, or lobes, roughly equidistant from the optical object. But these ''aperture synthesis'' telescopes are still limited in resolution. Even the largest of them has a maximum resolution of about one-third of an arc second — only slightly better than optical telescopes. In order to get substantially better resolution than this, the telescopes must be separated by much greater distances than a few kilometers. This is a problem because it is difficult to link telescopes over distances of, say, thousands of kilometers, and synchronize the signals to within a fraction of a microsecond.

Fortunately, by the late 1960s the advent of very accurate atomic clocks provided a solution to this problem. Using these clocks, it is possible to record the signals from two telescopes separately on videotapes with microsecond timing accuracy. The tapes are then shipped to a central processor where they are synchronized and the signals are combined. This is called very long baseline interferometry.

Here at Caltech we have had an active group practicing VLBI for the last ten years, led by Marshall Cohen, professor of radio astronomy, who was also one of the main founders of the field in the pioneering days of the late 1960s. Although VLBI looked promising at that time, it appeared at the start to be a limited technique, since, as in optical telescopes, all the waves must be coherent in order to make a proper image. Small scale atmospheric turbulence that upsets optical telescopes does not affect radio telescopes, but there are larger scale structures in the atmosphere that do affect radio telescopes. Ironically, these problems become severe over scales of a few kilometers at short wavelengths, that is, at just the scales and wavelengths at which radio observations begin to have resolution comparable to optical telescopes. The one-second resolution barrier applied to radio as well as optical ground-based observations!

The early VLBI observations were tantalizing — they showed that it was possible to achieve a resolution of 1/1000 of a second of arc, since interference fringes were observed, but due both to the atmosphere and to technical limitations, the position of the fringes jittered around in a random fashion. This made it impossible to add up all the signals coherently and hence to synthesize a large aperture and make a proper image. All we could do with VLBI was to make crude models of the active nuclei of quasars and radio galaxies, and face up to the fact that VLBI observations would never produce proper images (except perhaps in a very small number of special cases).

Or so it appeared in 1975. In that year we began ex-



Expanding to a network of three telescopes and interferometers (above) solved the problem of resolution limited by atmospheric interference. If the atmospheric cell over telescope 2 puts that signal out of step with the signals at 1 and 3, it does not affect the fringes of interferometer 13 (represented as a sine wave at bottom right), but it does shift the fringe positions on 12 and 23 by equal and opposite amounts. These cancel each other out, and the resultant closure phase gives a proper image of the source.

perimenting here at Caltech with a new approach to interferometry. Instead of considering *pairs* of telescopes, why not combine the signals from *three* telescopes simultaneously? With three telescopes — 1, 2, and 3 in the diagram above — there are three interferometers — 12, 13, and 23. If the atmosphere above telescope 2 delays the signal a bit, putting it out of step with the signals arriving at telescopes 1 and 3, this changes the position of the fringes on interferometer 12. However, it changes the position of the fringes on interferometer 23 by an exactly equal but opposite amount. The fringes on interferometer 13 are of course unaffected by what goes on above telescope 2. So, if we add up the fringe positions (or phases) around the loop, the shifts in position introduced by the atmosphere on 12 and 23 cancel exactly, and the "closure phase," that is, the phase summed around a closed loop, is unaffected. All the spurious contributions from the atmosphere and ionosphere, and from individual telescopes and electronics, cancel exactly. The closure phase reflects only the structure of the source.

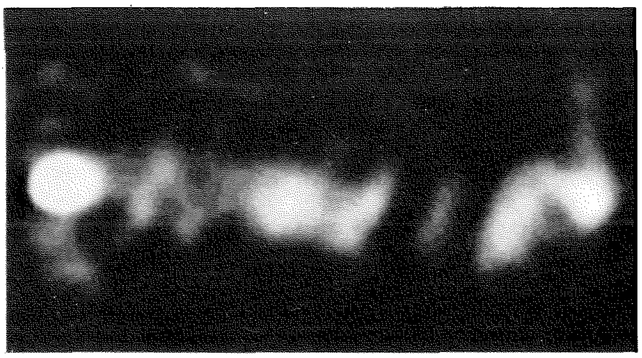
A generalization of this approach to a closed loop of four telescopes enables us to overcome difficulties in a similar way in measuring the size, or amplitude, of the sinusoidal signal, by measuring what we call the closure amplitude. These closure techniques use the object as its own phase reference and amplitude calibration, and we have developed a method for making proper images from completely uncalibrated and indeed uncalibratable data.

This breakthrough makes it possible now to synthesize telescopes thousands of kilometers across. For example, we would like to build a ten-telescope system that would reach from Hawaii and Alaska to the East Coast, using the earth's rotation to fill in an aperture 7,500 kilometers in diameter. Unfortunately, we do not yet have an instrument expressly designed for this function, but there are a number of telescopes built for other purposes scattered across the globe, and they can be used to test the feasibility of this scheme.

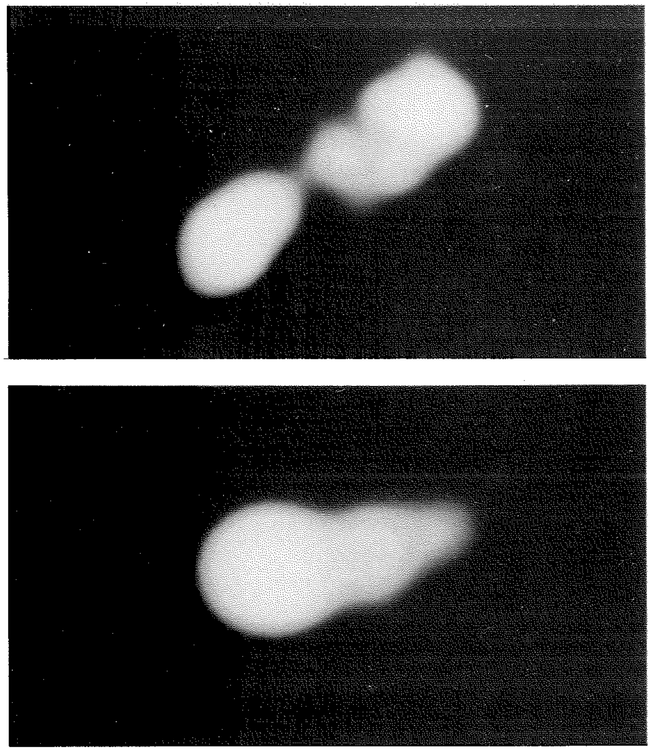
Using such a network of existing telescopes, we first applied this new approach in 1975 on the quasar 3C 147 (7 billion light years away) and succeeded in producing the first proper image of an astronomical object with a resolution of 1/100 of a second of arc. The next year we observed 3C 147 with a network of five telescopes. The jet in the image we obtained in 1976 is 2/10 arc seconds long, so the optical image would be an unresolved point one second across, that is, five times the size of the jet. We see that the quasar has a bright core and a one-sided jet about 5,000 light years long. We were very excited by these results for two reasons: First, they showed that it was technically possible to make proper images with VLBI — that is, we really can synthesize a telescope of global dimensions and make images with the full resolution that we would obtain in the absence of any atmosphere. Second, the results themselves were unexpected. We knew from initial work with aperture synthesis telescopes up to a few kilometers in size that the large-scale structure of radio galaxies and quasars is generally *symmetric*, consisting of two lobes roughly equispaced on either side of the optical object. In this distant quasar that we first mapped with VLBI we have an *asymmetric*, one-sided jet with a very bright core at one end.

The VLBI picture (below) does not show the full resolution of these observations. We can use the full resolution of 1/400 arc seconds on the core; and we find that it is a double source, which is aligned with the large-scale jet, with a separation between the two features in the core of only 50 light years.

Since 1976 we have observed a number of quasars, and

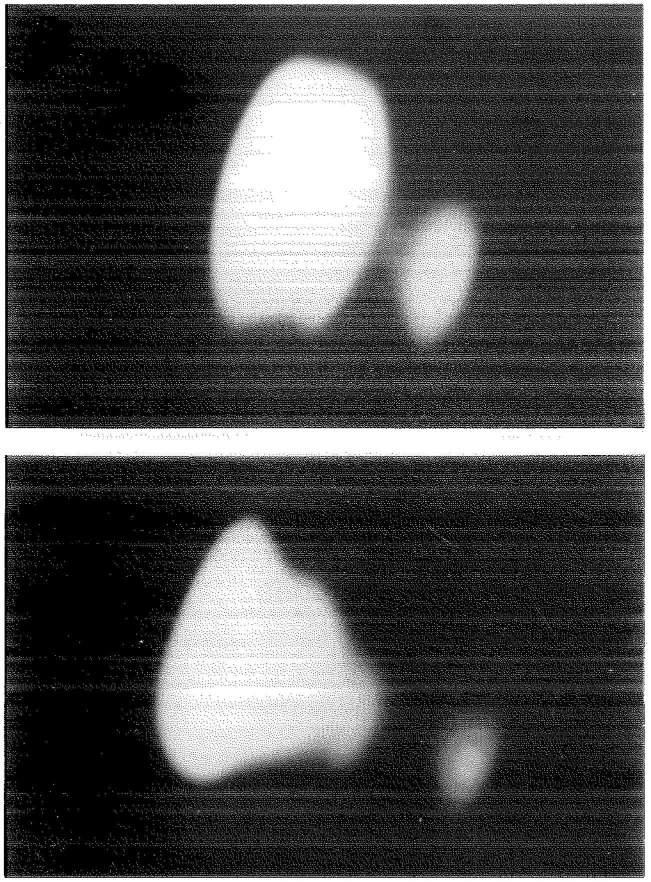


The first radio object to be mapped by VLBI was quasar 3C 147 — 7 billion light years away. This 1976 image with a resolution of 1/100 of an arc second showed a bright core with a surprising one-sided jet 5,000 light years long. The resolution of an optical telescope would have yielded an unresolved point one second across — five times larger than this jet.



Quasar 3C 380 (top), 8.2 billion light years away, is also a one-sided jet, although at this particular frequency the western knot in the jet is almost as bright as the core. The distance between the knot and the core — the two bright blobs — is 400 light years. In quasar 3C 345, seen here (bottom) with a resolution of 1/1000 of an arc second, the one-sided jet is about 50 light years long and is changing rapidly with time. Bright blobs are continually moving out toward the west and then fading away — at speeds apparently greater than the speed of light.

These images of quasar 3C 273 were made three years apart. In 1977 (top) the distance between the two blobs was 65 light years; in 1980 they were 92 light years apart. They appear to have moved 27 light years in three years or nine times the speed of light. This is called superluminal motion and is only an apparent speed, perceived because the blob is moving almost directly toward us.

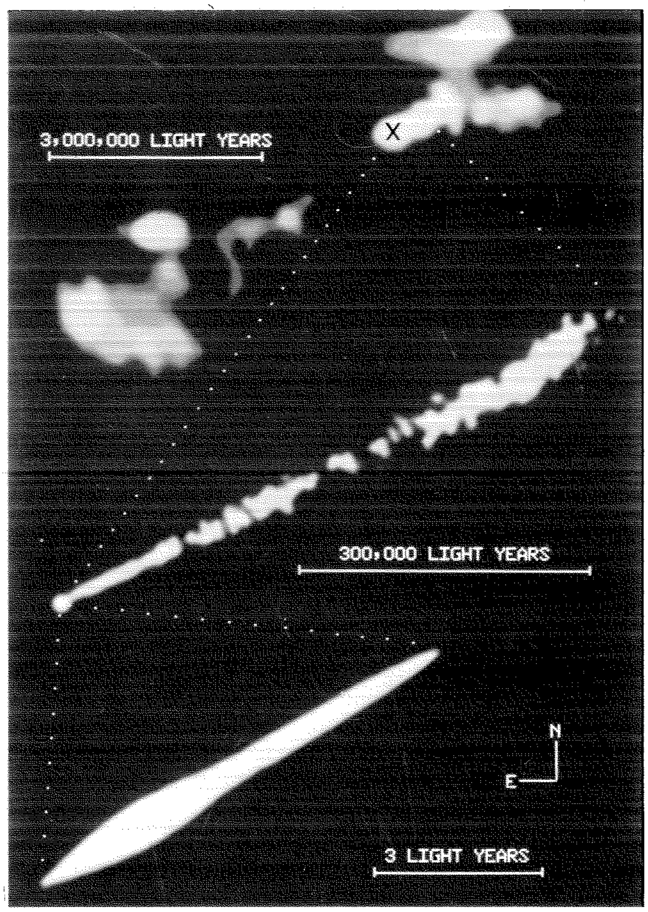


VLBI has revealed some extremely interesting features. We have seen 3C 345, also a one-sided jet, with a resolution of 1/1000 of an arc second. The jet is about 50 light years long and is changing rapidly with time. We continually see blobs moving out toward the west and then fading away. In an image made of another object — 3C 273 — in 1977, the distance between the two blobs was 65 light years. But in an image made this year, that distance is 92 light years. We also have observations from 1978 and 1979 that show the blob steadily moving out from the quasar nucleus. The extraordinary thing about these blobs in both 3C 345 and 3C 273 is the speed at which they *appear* to move. If the separation of the blob from the core of 3C 273 has changed from 65 to 92 light years, this is a distance of 27 light years in three years. So this blob is moving at an apparent speed of nine times the speed of light.

But this is only an *apparent* speed. The most likely explanation is that the blob itself is actually moving at slightly less than the speed of light, but close to it, and almost directly toward us. Because of the finite speed of light, this motion shows up as an apparent speed greater than the speed of light; Roger Blandford coined the term "superluminal motion" for this phenomenon. There is now a lot of other evidence that supports the above interpretation of this phenomenon.

It is remarkable that these quasar nuclei eject blobs of matter at nearly the speed of light and always in the same direction. What about the nuclei of radio galaxies? The best image we have obtained thus far of the nucleus of a radio galaxy is from a galaxy called NGC 6251 situated in a small cluster at a distance of 400 million light years. This object is by no means unique, but it provides a very good example of what we see in a number of extended radio galaxies and quasars. Optically this radio galaxy looks like a normal elliptical galaxy; however, radio observations reveal some fascinating properties of this object.

At right is a composite of three pictures of NGC 6251 made with three different radio telescopes giving three different resolutions. Note the different scales and the nesting of the two lower sections. The top image was made with the half-mile telescope at Cambridge, England. The optical galaxy itself is situated at the cross and occupies only a very small portion of this picture; the radio structure is similar to that of other typical radio objects. There are two major components straddling the galaxy, and the total size of the object is 6 million light years — about 60 times the diameter of a large galaxy. The region of the beam has also been observed at Cambridge with the five-kilometer telescope at higher resolution — about eight arc seconds — as shown in the middle picture. Here we see the beam along which matter and energy are transferred to the outer components. The length of this visible part of the jet is about half a million light years. The nucleus of the galaxy is coincident with the bright core at the eastern



Three views of radio galaxy NGC 6251 with different telescopes, different resolutions, and different scales. The entire radio galaxy (top) is about 60 times the diameter of a typical large optical galaxy. The center picture shows just the nucleus of this galaxy and the jet that carries matter and energy to the outer lobes. The lower frame shows only the core of the nucleus, which mimics the larger jet.

end of this jet. The galaxy itself only reaches out to about one-tenth the length of the jet in the middle portion. The core is unresolved by the Cambridge instrument, but using VLBI we have observed this nuclear source, as shown in the bottom portion. We see that the nuclear source mimics the structure of the larger jet on a scale 10^5 times smaller. The width of this jet is about one ten-thousandth of a second of arc — that is, equal to the width of a human hair seen at a distance of 50 miles. The visible part of the jet is about five light years long, and the brightness temperature is about 10^{12} K.

We can deduce some interesting properties of the galaxy from these observations. First, the total energy in these outer lobes is about 10^{61} ergs, that is, equivalent to the total annihilation of 10 million suns. In other words, the absolute minimum amount of matter that could give rise to the energy we see here has a mass of 10 million suns. On the other hand, if we consider ordinary thermonuclear burning, rather than total annihilation, we would have to increase this mass by a factor of 100.

Next there is the remarkably good alignment between this outer jet and the inner jet. This alignment, to within a few degrees, has persisted over at least the last million years — the time it would take matter traveling at the speed of light to reach the end of the jet. It only takes matter traveling at this speed a few years to traverse the inner jet. Thus, while an amount of matter comparable to a small galaxy has been expelled from the nucleus along this narrow beam, the alignment has not been disturbed. Physical arguments suggest that material is moving along the inner nuclear jet at nearly the speed of light. So the situation is similar to that in the quasars 3C 273 and 3C 345. In addition, the pressure required to collimate and confine a jet like this is very large.

Thus we have four stringent requirements of the object in the nucleus that is responsible for these radio features:

1) The object must produce a huge amount of energy to account for the energy in the outer lobes.

2) It must be very stable to account for the good alignment persisting over millions of years.

3) It must be able to eject matter at nearly the speed of light.

4) It must channel vast amounts of energetic matter into a narrow beam and withstand the high transverse pressure of the jet.

We know of only one class of objects that could satisfy all of these requirements, namely a spinning supermassive black hole of about 1 billion solar masses. We require it to be spinning so that gyroscopic action would make it very stable. If we imagine jets as coming out along the spin axis, this would account for the persistently good alignment. As we have seen, the object is required to produce enormous amounts of energy. A black hole in the galactic nucleus would use gravitational energy to power the radio source, and this is about 100 times as efficient as nuclear energy, so we do not need as much mass as we would if it were powered by nuclear energy. Finally, the high pressure and ejection of matter at nearly the speed of light would be most easily achieved in a relativistically deep potential well surrounding a black hole. Thus a 1 billion solar mass black hole is a conservative answer to what is going on in the nucleus of this galaxy. In a sense it is the minimal solution that can explain the observed properties of this remarkable object.

If this conclusion is correct, and there are indeed supermassive black holes in the nuclei of galaxies, then it is important to see if the observations allow us to learn anything about the space-time continuum around gravitationally collapsed objects. By pushing VLBI observations to higher frequencies, it appears very likely that we could achieve ten times the resolution that we have here. At this tremendous resolution of considerably better than a ten-thousandth of a second of arc, we would be able to look at the structure of some of these galaxies on a scale not much bigger than the size of the black hole itself. This would surely tell us whether the central object is indeed a black hole or some other beast as yet undreamed of. □