Double Radio Sources: Energetic Evidence That Galaxies Remember

Far larger than giant galaxies, which are in turn much larger than the Milky Way, are the hundreds of double radio sources that astronomers have found in the last 15 years. Like cosmic light bulbs glowing with radio wave emissions, these powerful radio sources are usually found on opposite sides of a giant galaxy. The peculiar objects have defied explanation in spite of the fact that they are among the largest and most energetic phenomena in the universe.

As improved radio telescopes resolve more and more detail of the double sources, their shapes and the distributions of radio intensities across their surfaces are becoming better known. Such measurements are showing that the strongest sources have clean shapes almost like dumbbells, while the weaker ones have much more diffuse structures that may only vaguely resemble two well-defined radio lobes. New interferometers with baselines on the order of a few kilometers, particularly the one at Westerbork in the Netherlands, have produced excellent maps of the largest features of the double radio sources. Quite different instruments, the very long baseline interferometers (VLBI) which consist of antennas separated by distances of thousands of kilometers, are providing information about the very small features of such radio sources (page 1263, this issue).

But some very important questions are still not satisfactorily answered. Why are the radio sources so often double, what provides the energy to make them so bright, how long have they been the way we now see them? There are at least three schools of thought that would provide different answers to these questions, and the only consensus seems to be that no model is without its flaws.

Astronomers do seem to be making headway, however, in solving the problem of the origin of these sources. Recent observations have shown that some of the small features are aligned with the large radio sources outside the galaxy. Particularly in the case of Cygnus A, a source in the Cygnus constellation, the small radio source is ultracompact and aligned in precisely the same direction as the large dumbbell-shaped source, but the sizes of the two features differ by a factor of 50,000.

The consensus of astronomers seems to be that what is observed on a small scale is either the formation of a new double radio source whose two components will move outward and expand in size until they form a large-scale double source or some mechanism that will replenish the energy of the old double source. The process of formation seems to take place in the nuclei of giant elliptical galaxies, and is apparently a recurring phenomenon. Furthermore, the fact that the old and the new doubles are formed in such a way that they are aligned on the same axis in space indicates that the galactic nucleus apparently has a directional memory that lasts for many millions of years.

New Telescopes Are the Key

Double radio sources are hardly new phenomena, as the first was discovered in 1953, and the enormous amounts of energy that must be released to power them were recognized shortly afterward, in 1956, by Geoffrey Burbidge at the University of California, San Diego. But the wealth of detail that is now becoming apparent on both very large and very small scales could not be seen until the present generation of very sensitive radio interferometers was built.

The preeminent facility for mapping the diffuse shapes of double radio sources is currently the Westerbork Radio Observatory, which has a 12-element interferometer that has been continuously upgraded since it started operation in 1970 (Fig. 1). The Westerbork interferometer combines the signals from the 12 individual radio antennas, by a technique known as aperture synthesis, to build up pictures of the radio signals coming from a rather large (by astronomical standards) region of the sky. In a typical observing situation, the telescope would "take" a picture covering 12 minutes of arc, with a resolution of 6 arc seconds, in about 12 hours. The Westerbork interferometer is particularly well suited to the study of extended double radio sources because it combines the features of fine resolution and high sensitivity to radio emitting regions with very low surface brightness. Maps of extended radio sources can be made with even greater resolution at the 5 km telescope at the University of Cambridge, England, but the Cambridge interferometer has less sensitivity to faint features than the Westerbork telescope, partly because it has only eight antennas. The Westerbork antenna also maps the full polarization characteristics of the incoming radio waves.

One of the recent discoveries with the Westerbork telescope is the radio source 3C236,* whose properties have stretched the imaginations and constrained the theories of many astronomers. The source is a sharply defined double radio structure that breaks all previous records for size by extending more than 18 million light years from one end to the other (Fig. 2). The radio source DA240, also shown in Fig. 2, is the second largest source known. For comparison, the Milky Way galaxy is about 100,000 light years across, and most clusters of galaxies are about 3 million light years in size. The radio emissions of 3C236 are produced by relativistic electrons as they spiral about the magnetic field lines locked into the dilute gases found in the radio lobes. The same mechanism—synchrotron radiation—is generally accepted as the explanation for radio emissions from all double sources. Thus the radio astronomers from Westerbork are probably not stretching the truth when they claim, like scientific P. T. Barnums, that the lobes of 3C236 are the "largest reservoirs of relativistic gas known to man." The central galaxy in the 3C236 system is a very bright radio emitter, strong enough to be listed in the '3C' catalog, and has been known for some time. But the huge radio lobes that constitute the double source are fainter and were just observed last year by A. G. Willis and associates at the Leiden Observatory, Netherlands.

The stupendous size of the double radio lobes of 3C236 also means that enormous amounts of energy, according to simple physical calculations, must be present in the clouds of gas. The internal energy in the lobes of 3C236, assuming the energy is equally distributed between the electrons and the magnetic field, must be at least 10^{60} ergs. This much energy is equivalent to the mass of a half-million suns, and it is likely to be a significant underestimate, as there are several plausible hidden contributions to the energy. For a less gigantic double radio source, such as the one in the Cygnus constellation, the stored energy would be at least 10^{58} ergs.

The huge amounts of internal energy found in a typical double source pose a difficult problem for theoreticians, not only because a significant portion of a galactic nucleus would have to be converted from

* The prefix 3C denotes an object in the third Cambridge catalog of radio zones, which contains all sources in the northern sky with flux densities above a certain, rather high, threshold. It is therefore the catalog of the brightest radio sources visible from this hemisphere.

matter to energy to "turn on" these clouds, but also because something must be at least partially confining the clouds or they would have expanded to more nearly spherical shapes and would be far larger than even the sizes observed. If the radio lobes contained only relativistic particles and magnetic fields, and were not constrained, they would expand at almost the velocity of light (c\ 3). But if they somehow propagated out from the parent galaxy, the fastest they could have traveled was at the speed of light. So it is very hard to see how the radio lobes could have maintained their small sizes, relative to their separations, unless something stopped them from freely expanding. Astronomers generally assume that either the radio clouds are slowed down by the inertia of a hidden mass of material that does not produce radio emissions, or else their expansion is impeded by the resistance of intergalactic gas. There are problems with both explanations, but the hidden mass hypothesis is particularly troublesome because it raises the ante in the energy problem considerably more.

Several lines of argument suggest that the energy found in the radio clouds was not supplied in a single burst when the cloud was ejected from the parent galaxy, but must have been supplied either intermittently or continuously. As the clouds expanded during their presumed evolution from small galactic features to the present supragalactic scale, they must have cooled adiabatically. Therefore the radio emissions would decrease. But the small radio sources observed are far too faint to undergo such cooling without practically disappearing from the radio sky. If the large lobes in Cygnus A were to be compressed to the scale of a galactic nucleus, they would be 10^6 times brighter than the nuclear radio sources that have been observed. For the supergiant, 3C236, the problem is even worse. According to Harry van der Laan, of the Leiden Observatory, no one has found a way to fill the bottle with plasma and cosmic rays (electrons) if they originate in the core of a compact nucleus. In the course of being distributed over the large volume, more than 99 percent of the energy will be lost according to current treatments of cosmic ray propagation.

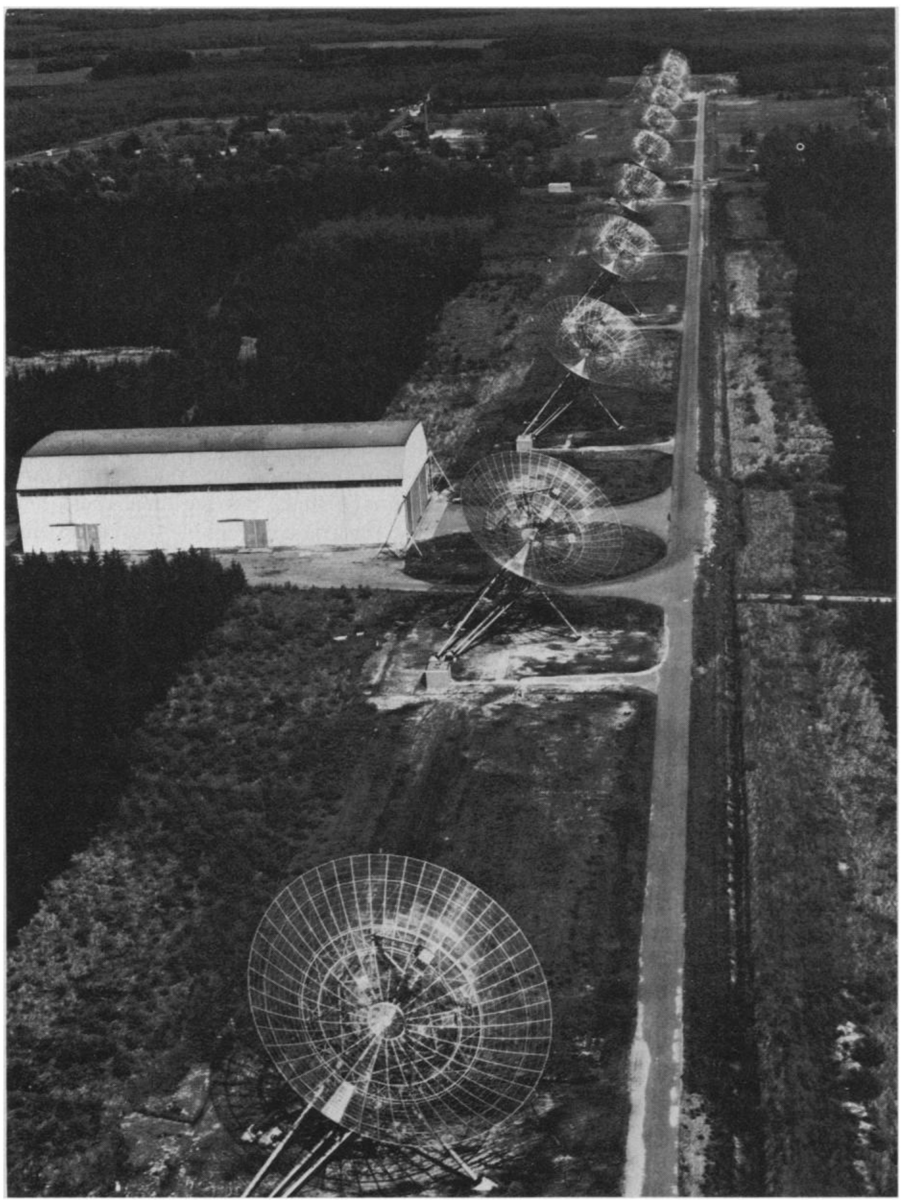


Fig. 1. The aperture synthesis radio telescope in Westerbork, Netherlands. The instrument is an interferometer composed of 12 antennas, each 25 meters in diameter, placed along an east-west line. The total length, or baseline, of the instrument is 1600 meters. As the earth rotates, the orientation of the array changes in relation to the sky, and in the course of 12 hours an effective aperture of 1600 meters in diameter is synthesized. The large shed was used for assembly of the telescope antennas. Note the reflections of sunlight from the stainless steel mesh of the antenna surfaces. [© Aerophoto Eelde, Netherlands]

Another problem with energizing the radio lobes with an initial explosive event is that it would require a level of power production that is unprecedented, even in the annals of astrophysics. The total power necessary to produce 3C236 in a short burst—the time scale proposed for theories of this type is less than 1000 years—would be more than 10^{43} watts, which is four orders of magnitude more than the output of active giant galaxies and quasars, and six orders of magnitude greater than the power radiated by our galaxy over all wavebands. An explosion of such violence, occurring in any circumstance now visible from earth, would dramatically outshine even the brightest quasars and radio sources known.

Yet another problem with the idea of energizing the radio sources in an initial burst is that the expected lifetime for the electrons in the clouds to emit synchrotron radiation is less than the travel time for the large clouds to reach their present positions (generally thought to be 10^6 to 10^8 years). If the injected electrons slow down and stop emitting strong radiation before the clouds reach full size, then it would seem that there must be some sort of particle accelerator in the radio source that replenishes the lost electrons.

The particle accelerators could be stars nearing collapse, stellar-mass black holes, pulsars, or massive objects located in the radio lobes. So far there is no evidence that compact objects are present in the radio lobes, but the idea is quite appealing because of its similarity to the situation in the Crab nebula, where one pulsar provides all the relativistic electrons necessary to keep the whole nebula glowing with visible as well as radio emissions. Evidence for compact objects could come from radio observations made with very long, typically transcontinental baselines. Such VLBI instruments have found the very small (1 millisecond of arc) radio sources located in the parent galaxies of the gigantic sources, and more observations of the radio lobes themselves are also needed, according to Roger Blandford at the University of California, Berkeley. The possibility that small objects that emit visible light are present in the radio lobes cannot be ruled out either, according to David De Young at the National Radio Astronomy Observatory (NRAO), because more observations are needed with the most sensitive optical techniques available.

One way in which small massive objects could be ejected from the parent galaxy is called the gravitational slingshot model. By dynamical interactions in the nucleus of a galaxy, two objects could be ejected in one direction and then the third object would be ejected in the opposite direction. This model has been recently suggested by William Saslaw, of the University of Virginia, Charlottesville. Although the model succeeds in explaining how objects could be ejected in antiparallel directions, it predicts that they would be found in the equatorial plane of the galaxy, which is not always the case. In Centaurus A, for instance, the double radio lobes are aligned with the rotational poles of the galaxy, not the equator.

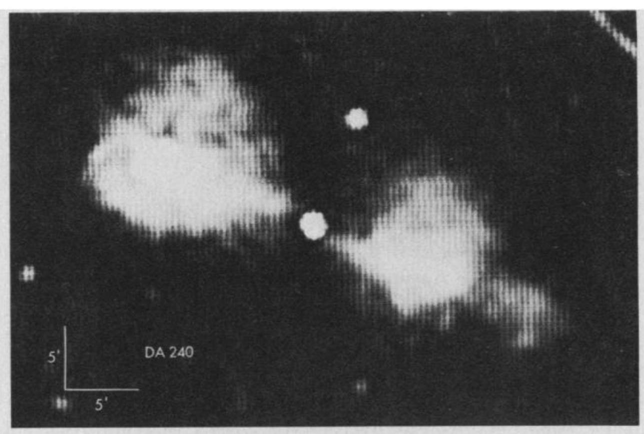
A still more powerful argument against the gravitational slingshot model is the discovery that many double radio sources have several structures that are well aligned. It's repeatability of the energizing mechanism that is so striking, according to Burbidge. Since the slingshot effect depends on random encounters, it would sprinkle objects throughout the equatorial plane rather than eject successive objects along virtually the same line. But in several cases, the most compact galactic radio emitters are found oriented along the line between the external lobes within a few degrees error, even though the distance scales differ by 10^5.

The newly discovered alignments of macro- and microscale radio structures not only weigh against the slingshot model, but put considerable constraints on all potential models. Five sources are now known to have clearly aligned structures, with ratios varying from 10^2 to 10^5, and more are likely to be found. Using very long baseline interferometers, Kenneth Kellermann at NRAO and associates at NRAO and the Jet Propulsion Laboratory in Pasadena, California, have found aligned radio structures, extending only a few milliseconds of arc, associated with the double radio sources Cygnus A, 3C111, 3C154, and 3C147. The compact sources are elongated in shape and consistent with the typical size of a galactic nucleus, a few light years.

The giant source, 3C236, does not so far seem to have any aligned structure on the scale studied by very long baseline instruments, but structure has been discovered at an intermediate size, about 5000 light years, that is somewhat less than the full extent of the elliptical parent galaxy. Using the 35 km interferometer at NRAO, Ed Fomalont and George Miley have mapped a faint radio source that is 0.7 second of arc long, quite thin, and well aligned with the very large double structure. The entire angular extent of 3C236 is 38 minutes of arc. According to Fomalont, the small source is clearly "doublish," but is somewhat asymmetric. An intermediate size double has also been found in 3C154, by Kochu Menon working with the Ooty telescope in India.

The first double-double, as they are sometimes called, was really the radio source Centaurus A, which is only visible from the Southern Hemisphere. This source is among the nearest galaxies and therefore has a huge angular extent. But the largest scale structure of Centaurus A is a rather relaxed double shape, and the alignment of the inner double shape with the outer one is therefore less impressive than in the more recently studied sources.

The quest for a mechanism that could produce consecutive double sources—at intervals of 10 million years or more, on almost exactly the same axis—is certainly not complete. Most astronomers agree that the only thing that seems intuitively reasonable as a physical reference that will maintain its alignment for such a length of time is the rotation axis of the galaxy, or still better its nucleus, which is presumably related to the radio phenomena. One astronomer said, "If only I could find a way to eject condensed matter along the rota-



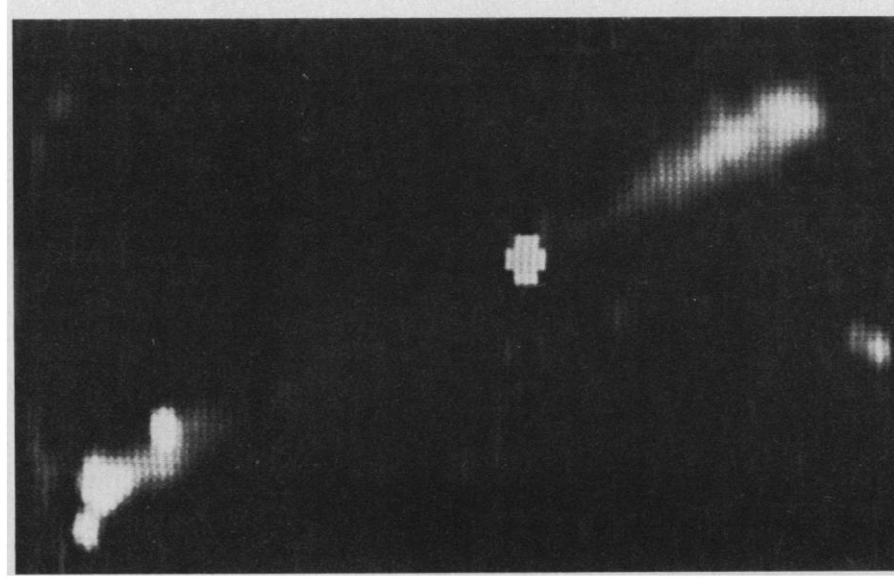


Fig. 2. The two largest objects known in the universe, shown approximately to scale. The two lobes of the radio source DA240, upper right, extend over a distance of 6 million light years, which is about ten times the distance to the Andromeda galaxy. Radio source 3C236, below, extends more than 18 million light years. Both objects are called double radio sources because they consist of two radio-emitting clouds located on opposite sides of a visible galaxy. In the computer-generated "radiograph" of 3C236, the position of the galaxy is marked by a cross. A much smaller radio structure, not shown here, has recently been found at the position of the cross in the 3C236 system, oriented along the line between the two large clouds. The smaller structure is less than one-hundredth the size of the computer-generated cross. [Source: Westerbork Radio Observatory]

tion axis, it would be a very appealing explanation."

But to measure the rotational axis of the nucleus alone is a terribly difficult observational problem, and there is no conclusive evidence that the radio structure is aligned with the rotational axis of the galaxy as a whole. According to van der Laan, "At first they thought the rotational axis was aligned with the radio structure, then they thought it was at 90°, then biomodal; as more and more data come in it looks like a random distribution." The structure could nonetheless be aligned with the nuclear axis, because the attractive assumption that the nucleus and the galaxy might spin about the same axis is not necessarily valid. Even with a mass of 10^9 suns, a typical nucleus would only carry a small fraction of the angular momentum of the rest of the galaxy if it contracts to nearly black hole proportions.

One way to eject uncondensed matter from the center of a galaxy has been proposed by Bob Sanders at NRAO. He found that if an explosion occurred in the center of a massive nucleus (10^8 solar masses), the debris would come out along the rotation axis. The distribution of matter in the massive nucleus would collimate the debris so that it sprayed out in a cone-shape at either rotational pole.

Other types of models do not postulate that there are stars, debris, or black holes in the radio lobes, but would continuously supply the needed energy with something like two beams of cosmic rays emerging from the galactic nucleus. Such models put the energy source that drives the radio emission back in the center of the parent galaxy, and leave it to the reader to decide whether spinars, massive black holes, or huge numbers of ordinary stars, in the process of collapse, provide the power.

One particularly well developed model using two beams to provide power has been proposed by Blandford and Martin Rees, at the Institute of Astronomy, Cambridge, England. In this model, the unspecified energy source is assumed to steadily produce a hot plasma that flows out in two streams along the rotational axis, because the pressure falls off most rapidly there. The pressure profile in the center of the galaxy also determines the shape of the stream, and in fact a nozzle can be formed where the pressure has dropped to half its central value. Beyond the nozzle, the flow of the plasma will become supersonic, which is also a highly relativistic speed for environments where the gas density is only a few particles per cubic meter. The outgoing beams are thus highly collimated, and evacuate a channel in the intergalactic medium by continually forcing it out of the way. The hot spots observed in the lobes of double radio sources such as Cygnus A [*Science*, **188**, 1077 (1975)] are interpreted to be the places where the beams are currently encountering the external medium, setting up shock waves, and regenerating relativistic electrons.

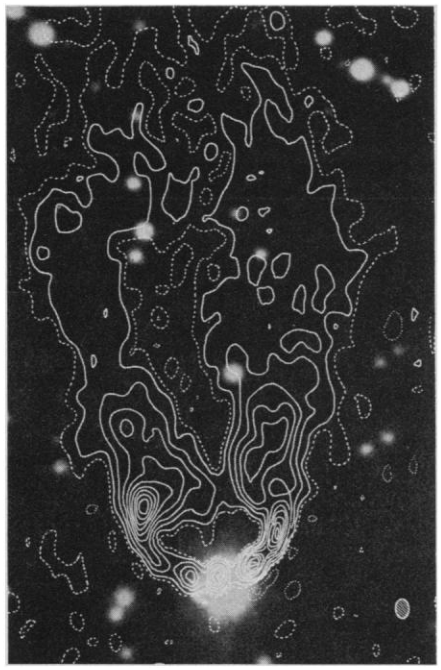


Fig. 3. The white contour lines indicate the radio signals that are emitted from the region behind the galaxy NGC 1265, shown superimposed on the radio data in the lower part of the figure, as it moves through space. The radio trails are believed to be caused by relativistic particles ejected from the galaxy as much as 1 billion years ago. At least two radio "hot spots" are found on either side of the visible galaxy. [Source: Leiden Observatory]

The most appealing aspect of the Blandford and Rees model is that it explains the bifurcation of the energy supply and the binary structure that is characteristic of so many strong radio sources. But some astronomers question whether the pencil beams of relativistic particles would remain so tightly collimated over distances of millions of light years. The stability of the situation is very difficult to calculate, and so far no one has checked it. Another problem, according to De Young, is that the relativistic beams should pile up material at the edges of the cavity and make the outer portions of the radio source brighter than the middle—limb brightening. But such a condition is not observed.

Almost all of the models fall short, at the present time, of explaining the observations. Particularly because of the discovery of the hierarchies of aligned radio structure, the observationalists seem to be in ascendancy right now, and there is clearly much more material that can be added to the data on the subject. The data reported in this article were obtained in a relatively short span of time—most of it in the last year. There is every reason to think that the new generation of interferometers will produce much more data of similarly high quality. The Cambridge Cavendish Laboratory, under Martin Ryle, has embarked on a program of high resolution studies of the 100 brightest sources in the 3C catalog. In addition to the new capabilities for high resolution, the new short baseline interferometers are proving excellent for polarization and spectral studies.

A good scientist can often seize upon the certain clear-cut phenomena long before the proper interpretation is known, suspect that they are important, and extrapolate their implications. While no one really knows what it is that ejects double clouds of relativistic electrons from a giant galaxy to produce double radio sources, some astronomers are already postulating that the same mechanism also produces the phenomenon of radio trails that appear behind a galaxy moving through the medium that is found in a cluster of galaxies (Fig. 3).

Whereas the galaxies that produce double radio sources are thought to be moving rather slowly, galaxies in clusters may be moving quite a bit faster. The source NGC 1265 in the Perseus cluster is estimated to be moving several thousand kilometers per second. If there is more intergalactic gas inside clusters than elsewhere, as x-ray observations suggest, then the gas would be expected to create a drag on radio sources ejected from a rapidly moving galaxy and produce the configuration in Fig. 3. This high resolution map from the Westerbork telescope seems to show at least two pairs of bright spots on either side of the optically visible galaxy that could be the same phenomena as double radio sources, shaped by the bow shock wave formed as the galaxy ploughs through the intergalactic medium. The more amorphous contours far from the galaxy are assumed, in this rather speculative connection, to be from much older radio lobes that have long since been smoothed by the interaction with the outside medium. The great length of the radio trails associated with NGC 1265 seems to indicate that the mechanism that ejects clouds of relativistic particles from a galaxy may continue to operate for as long as 10^9 years.

Of course, radio trails may not be related to double radio sources. But many astronomers tacitly assume they are similar, and the assumption seems consistent with the principle of constructing the minimum number of different mechanisms to explain the observations.

—William D. Metz