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Jets in Extragalactic Radio Sources

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Summary. Observations now require that there be a continuous supply of energy to the giant extragalactic radio sources. These observations also suggest that this energy input may be in the form of streams or jets of gas emanating from the centers of galaxies and quasi-stellar objects. Current data indicate that the large-scale jet structures are not moving with relativistic speeds, as previously proposed. Slow-moving jets, which possess turbulent interiors and are dominated by relatively cool gas, can account for the observed jet properties at optical and radio wavelengths. Extremely small-scale jets observed adjacent to the central energy source may or may not be in relativistic motion.

Nearly three decades have passed since the discovery that many galaxies and quasi-stellar objects (QSO's) emit radiation at radio wavelengths. This radio emission is seen in two general locations. The first is a very small, bright region located in the very center of the galaxy or QSO, and the second is a double-structured region lying on either side of the associated galaxy or QSO. The size of this second class of radio-emitting volumes may range from dimensions comparable to a galaxy to regions of order a hundred times the size of the parent galaxy. Very often both kinds of structures are observed, and Fig. 1 shows a typical example of such a radio source as seen at radio wavelengths. The bright central cores or compact sources are quite small by astronomical standards, of order 1 parsec (3×10^{18} cm), whereas the large extended sources may be up to a million times this size. The total power radiated at radio wavelengths by the extended sources ranges from 10^{42} to 10^{46} erg sec^{-1}; the higher value is 100 times the energy radiated by all the stars in a typical galaxy. The enormous size and power of the extended radio sources make them unique: they are the largest single objects in the universe, and they contain very large amounts of energy in a very specialized form.

In all cases the radio emission from both compact and extended sources is almost certainly due to incoherent synchrotron radiation from an ensemble of relativistic electrons embedded in a magnetic field. Most of the radio frequency power lies in the range $\sim 10^2$ to 10^4 MHz, and the spectrum of the radiation is that due to an electron population with a power law distribution in energy (*1*).

The size and power of the extended sources lead immediately to speculation about how such large amounts of energy are produced, particularly in the specialized form of relativistic electrons and magnetic field, and how this energy can be transported over such great distances. Motivated by morphology similar to that shown in Fig. 1, investigators proposed in an early model (*2*) for the extended radio sources that two oppositely directed clouds of relativistic electrons, magnetic field, and cooler "thermal" plasma be ejected from the parent object by a gigantic explosion. The characteristic shape of the radio source would then arise from the ram pressure exerted by the surrounding medium on the cloud as it passes through at supersonic speeds.

However, subsequent observations have shown this kind of model to be inadequate in one important respect. For many extended radio sources, if the relativistic particles were ejected from the parent object in a single event, they would lose energy too rapidly to be either seen where they are seen or to be radiating at the highest frequencies observed. This means that all viable radio source models must provide for a continual replenishment of energy in some form. This "lifetime" problem can be seen to arise in a simple way. The frequency at which an electron radiates in this process is proportional to the square of the electron energy; thus, as the energy is radiated away, the frequency of the radiation decreases. Conversely, if the initial electron energy is known, the length of time it can radiate at a given frequency can be found. Although the initial electron energies are not known, minimum electron energies can be estimated, and these can be coupled with observations at very high frequencies to search for the frequency above which the radiation should abruptly decrease. Such cutoffs have not been found even at millimeter wavelengths (*3*), and this in turn implies net lifetimes of 5×10^9 years for nearby sources.

Given this limit on the lifetime, an overall radio source size of 1 megaparsec then requires that the energetic electrons must have traveled from the nucleus to the extreme edges of the source with average speeds of one quarter the speed of light, *c*. Sources up to 4 megaparsecs in size have been observed (*4*). Although only about 5 percent of all radio sources are 1 megaparsec or more in size (*5*), these exceptional sources present a severe lifetime problem.

More extreme cases are found in two nearby radio sources. The first is the giant elliptical galaxy NGC 4486, which lies at the center of the Virgo cluster of

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galaxies. This well-known radio galaxy exhibits a jetlike structure emanating from the nucleus, which contains "knots" or condensations of radio emission. The key feature is that these knots are also seen at optical wavelengths where they exhibit a blue, featureless continuum spectrum that is strongly polarized. The optical appearance strongly suggests that it is also due to synchrotron radiation; if so, the extremely high frequency of the radiation implies a very short radiative lifetime. This estimate can be made very quantitative if we use the best values for the magnetic field and particle energy recently obtained (*6*). These give a lifetime of ≈ 100 years. The radio and optical structure extends at least 1 kiloparsec from the nucleus (neglecting projection effects); hence the electrons would have to travel from the nucleus at speeds in excess of 30 times the speed of light in order to arrive at the end of the jet within their radiative lifetime.

This impossible situation is also found in the nearest radio galaxy, NGC 5128, where jetlike structure is seen in both radio and x-ray wavelengths (*7*). If the x-ray emission is electron synchrotron, then again lifetimes of ~ 100 years result, and these are less than one-tenth the travel time of light from the nucleus.

Thus these observations, together with other morphological properties of radio sources to be discussed below, have led to an inescapable conclusion: that the electron energies, if not the energetic electrons themselves, must be replenished throughout a considerable fraction of the radio source volume on a more or less continuous basis.

Jet Models

Motivated by the observations which demand in situ replenishment of the electron energy in radio sources, the basic idea underlying jet models is that there be a continuous, collimated outflow of energy from the nucleus to the radio source. An early version of this idea (*8*) proposed energy transport in the form of a highly collimated beam of electromagnetic radiation. This model failed to produce the observed polarization pattern of the radio emission and also suffered from difficulties in explaining how the beam was produced. A modification of this model was developed (*9*) and has become the "standard" beam or jet model. This model begins with the assumption that deep within the nucleus of the parent galaxy or QSO some (unspecified) process produces a steady amount of very hot, relativistic plasma and perhaps

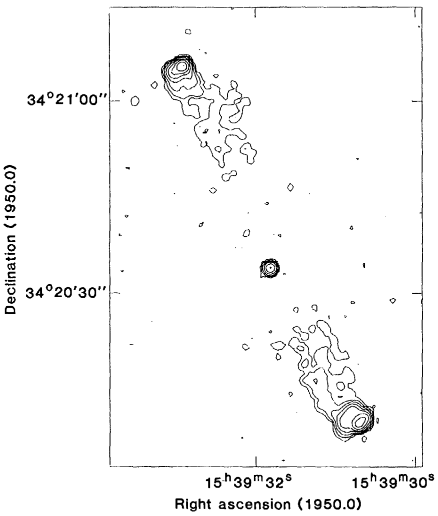

Fig. 1. Radio contour map of the radio source 1539 + 343 made at a wavelength of 6 cm with the Very Large Array. The radio source is associated with a distant galaxy with a red shift of 0.402. The overall extent of the source is 486 kiloparsecs, or about 20 times the size of the parent galaxy which is centered on the bright core of emission between the two lobes. The luminosity of this object at radio wavelengths is approximately 10^{43} erg sec^{-1}. [From (*11*)]

some magnetic field. Surrounding this region is a relatively cool ($\sim 10^8$ K) and dense ($\sim 10^3$ cm^{-3}) cloud of gas that is flattened by rotation. The hot relativistic gas inflates a cavity in this cloud until the pressure becomes sufficient for the gas to escape. Given rotational symmetry in the confining cloud, the path of least resistance lies along the rotation axis, and two oppositely directed streams of outflowing gas will be produced. Steady-state solutions to the Bernoulli equation have been found for this flow, given that the initial pressure distribution in the confining cloud is known. The solution provides a pair of oppositely directed Laval nozzles formed in the confining cloud, and, as the relativistic gas moves through these nozzles, its thermal energy is transformed into highly collimated, relativistic outflow with a very low internal temperature. Typical parameters for this "central engine" are a nozzle radius of ~ 10 parsecs and a nozzle length of ~ 200 parsecs, with a power output of $\sim 10^{45}$ erg sec^{-1}.

The subsequent propagation of the jets in this model has been developed in a more qualitative manner. It is assumed that the relativistic motion continues outward until it is stopped by interaction with the surrounding intergalactic or circumgalactic gas. This interaction occurs through a shock pair, the first being a bow shock propagating ahead of the jet termination and the second a shock internal to the jet through which the material in the jet is decelerated. This shock pair configuration is a well-known hydrodynamic phenomenon, and it is important to note that the end point of the jet propagates outward more slowly than the flow of material in the jet. The internal shock provides a means of converting the directed relativistic motion to near random relativistic motion of the particles. This is a necessary feature because the observations are not consistent with large-scale ordered motion of the relativistic electrons.

This basic jet model has several immediate advantages. It directly solves the lifetime problems described above. Moreover, a cold beam of particles moving at relativistic speeds is an extremely efficient way to transport energy. Thus the model places the minimum energy production requirements upon the central energy source in the nucleus. The model provides in a natural way for the high-intensity "hot spots" often observed near the leading edge of double radio sources; these would arise at the shock front where the flow becomes thermalized. After this thermalization, the relativistic electrons flow back around the jet as seen in a frame comoving with the jet terminus, and this "cocoon" of radiating particles can provide the bridge of emission that is often seen extending from the end of the source back toward the parent object. Last but far from least, the model provides in a very natural and fundamental way a means to produce the basic double structure seen in almost all extended radio sources.

Are Large-Scale Jets Relativistic?

Although the relativistic jet model has many virtues, recent observations provide evidence that it may require significant modification. Figure 2 shows the radio emission from a member of an important class of radio sources known as "head-tail" radio galaxies. These radio galaxies occur in clusters of galaxies, and it is believed that the radio morphology results from the continuous outflow of energetic particles being swept back by the ram pressure of the hot intracluster gas as the galaxy moves through this gas.

The radio map in Fig. 2 exhibits properties of great interest when one is considering relativistic flow models. The radio emission consists of several bright knots close to the nucleus that are linked by curved bridges of emission, and the problem that objects such as this pose for relativistic flow is fundamental. The model is based upon a beam of cold, collimated particles that emit synchrotron radiation when randomized by a shock at the end of the beam. Bright knots near the nucleus must imply, in the context of this model, disruption of the orderly flow long before it reaches the outer regions of the radio source. If this disruption occurs, how does the flow proceed beyond it in order to supply energy in the more removed portions of the radio source? Further, one must ask how a series of such knots can occur. Bright knots in linear arrays are not uncommon in extended radio sources (*5*), and it has been suggested that they arise from the sweeping up of interstellar clouds by the relativistic jet (*10*). In order for this process not to disrupt the jet, the cloud size must be much less than the cross section of the jet, and it is not clear whether the model parameters can be adjusted to accomplish this in all cases. Moreover, a continuous supply of clouds is required, yet very little interstellar gas is seen in the class of elliptical galaxies that produces extended radio sources.

Figure 3 shows another example of a very common type of radio source, a basic double with a bright jet on one side. Several elements are of importance, and these features are quite common (*5*); the brightest portion of the jet is nearest the nucleus, the jet is bent, and there is no bright spot at the end of the jet. None of these features would be expected in the standard relativistic flow picture. In order to bend a relativistic jet, some obstacle must be encountered, and such an encounter will inevitably produce shock waves. Thus it would be expected that a bright spot would occur whenever a bend is encountered, contrary to what is observed. There exist many radio sources with two oppositely directed jets similar to the one-sided jet shown in Fig. 3, and the general morphological characteristics of all these sources, which argue against relativistic flow, are high brightness features near the nucleus, generally strong radio emission all along the jet, lack of bright spots at the end of the jet, and bending or curvature of the jet. Indeed, the outermost features of the sources shown in Figs. 2 and 3 and in several other sources, are suggestive of gentle, subsonic drift motion—far removed from what would be expected from the supersonically propagating termination point of a relativistic jet.

However, there do exist extended radio sources that are composed of two well-defined bright regions with sharp boundaries and no visible bridges of emission extending back to the nucleus. Such sources are still consistent with the relativistic jet model, and a question arises as to the existence of two distinct classes of radio source. That is, do there exist truly "quiet," efficient beams of energy propagating away from the central engine, or is there some "noise" or inefficiency in the energy propagation for all radio sources? The resolution of this question will require long observing periods with the most sensitive radio telescopes. Preliminary results (*11*) indicate that all sources may have observable radio jets. The principal conclusion is that for a great number of extended radio sources the jets are not cold, quiet, and relativistically propagating, and that the basic beam model does not apply to them. Current indications are that it may not apply to any extended radio source.

The Consequences of Large-Scale Slow Jets

The principal drawback to abandoning relativistic flow is the loss of efficiency and the consequent increase in the energy output required by the parent galaxy or QSO. This problem will be addressed subsequently, but it is important to first point out that slow jets can have significant virtues. The jet shown in Fig. 3 displays synchrotron losses all along its extent, and it is now clear that for the most lengthy examples of such jets there must be continuous reenergization of the electron population within the jet itself. This is a result of the lifetime arguments discussed above, and it shows that there cannot be efficient transport of energy to the end of the jet but that rather there must be a continual diverting of jet energy to the electron population all along its length.

For inefficient jets this energy input can arise in a natural way. The morphology of radio sources shows that there must exist a tenuous intergalactic or circumgalactic gas around the radio sources, otherwise the particles and field would be freely expanding into a vacuum and would not appear as they do (*12*). If the jet is moving supersonically but nonrelativistically, it is well known that for the high Reynolds number flow involved the jet interface with a surrounding gaseous medium is transacted via a turbulent boundary layer. (Although very little is known either experimentally or theoretically about relativistic jets, it would seem that some sort of turbulent boundary layer must exist for these jets as well. It may be that a quiet, efficient beam can exist only as a naïve theoretical construction.) Suppose the jet were to contain not only relativistic particles and magnetic field but significant amounts of

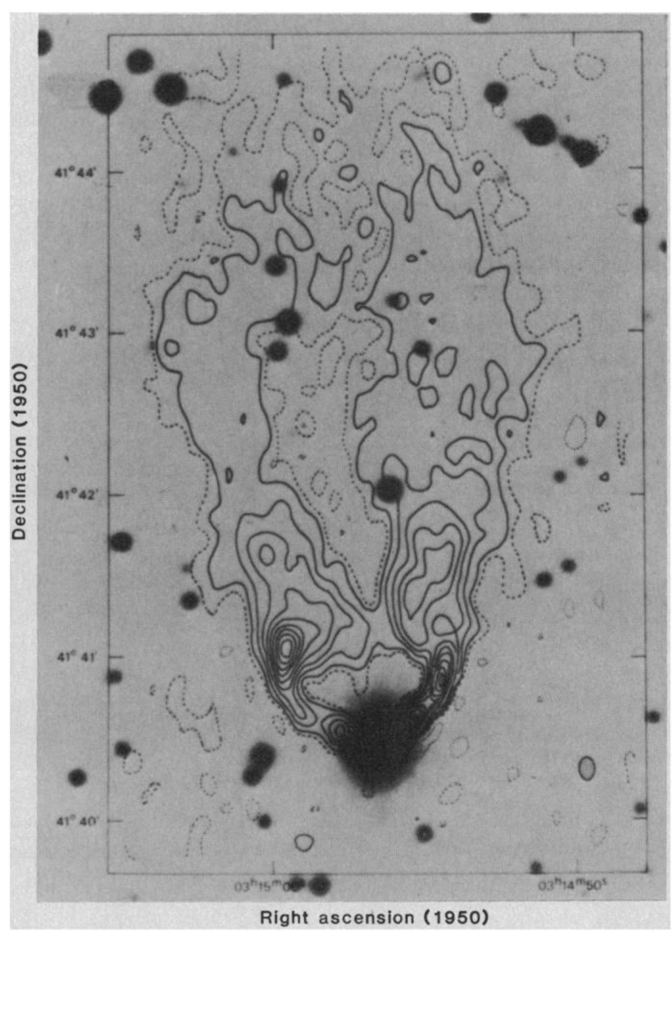

Fig. 2. Head-tail radio source associated with the galaxy NGC 1265 located in the Perseus cluster of galaxies. The radio contour map at 6-cm wavelength is superposed upon an optical photograph of the region. [From (*23*)]

cooler ($\sim 10^6$ to 10^8 K) gas as well. If most of the kinetic energy is carried by this cool gas, then in a turbulent boundary layer there exist numerous stochastic acceleration processes (*13*) which can serve to reenergize the electron population along the jet as required by observations.

Slow turbulent jets dominated by nonrelativistic gas may explain another recently observed feature associated with radio sources. Astronomers are finding an increasing number of radio sources which are coexistent with regions emitting spectral lines at optical wavelengths that indicate the presence of "heavy" elements such as sulfur and nitrogen (*14*). These lines are often seen well beyond the optical image of the parent galaxy, that is, outside the stellar population; yet such elements have clearly been through nucleosynthesis for their formation. An immediate question is how they came to be so far removed from their presumed site of production in the interstellar medium. A possible answer can be found in their association with radio sources, all of which fall in the "inefficient" class. The outflow that powers the radio source originates in the center of the parent galaxy or QSO, and, if a turbulent boundary layer develops, it must entrain gas from the interstellar medium or QSO envelope as it passes through. This entrained gas, which is rich in heavy elements, is shock-heated by the leading edge of the jet and may cool to the line-emitting temperatures of $\sim 10^4$ K only after it has been transported far beyond the stellar population that produced it. A more detailed consideration of this entrainment process (*15*) shows that it may also account for the presence of very young stars located along the edges of a radio jet in a nearby radio galaxy.

A final virtue of slow inefficient jets is that they may provide a means of supplying the required magnetic field for the extended radio sources. In the relativistic jet model and in radio source models in general, more attention has been paid to relativistic particle production than to magnetic field generation. Yet in the minimum energy configuration the energy density is comparable for both, and there is a need to understand how the required magnetic field comes about. If the energy transport from the nucleus is dominated by slow, relatively cool jets that are turbulent and that also produce turbulence throughout the radio source volume, then amplification of a dynamically unimportant seed field is possible. A fully nonlinear but geometrically restricted calculation of seed-field amplification by such turbulent processes shows that such a mechanism may produce the required field strengths (*16*).

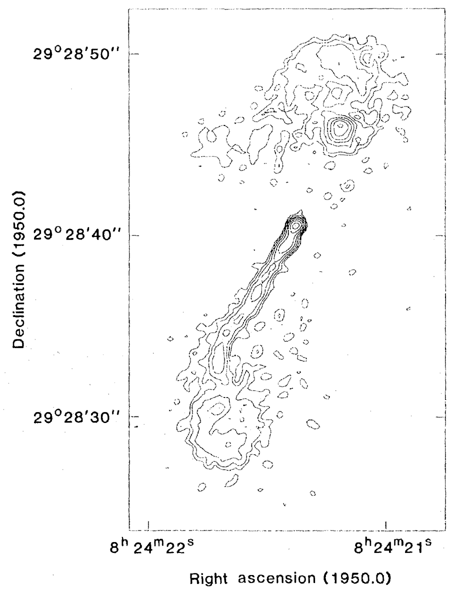

Fig. 3. Radio contour map of a double source with a large-scale jet at 6-cm wavelength. The parent object is a galaxy with a red shift of 0.458, and the galaxy is centered at the bright end of the jet. The power being emitted by the jet is 7×10^{42} erg sec^{-1}, and the overall radio luminosity of the source is 2×10^{43} erg sec^{-1}. [From (*11*)]

The energy requirements for slow inefficient jets are simply calculated. Most stochastic particle-acceleration mechanisms proceed with rather low efficiency, of order 1 to 10 percent, although some shock-acceleration processes can proceed with efficiencies of order unity (*17*). Magnetic field amplification proceeds with efficiencies of 1 to 10 percent. If ϵ is the net efficiency of converting bulk kinetic energy into relativistic particles and field ($\epsilon \leq 1$) and if L is the radio luminosity of the source, then energy balance requires $L = \epsilon \rho v^3 A$, where ρ is the gas density in the jet, v is the jet velocity, and A is the jet cross-sectional area. A nominal luminosity could be 10^{44} erg sec^{-1}, and a nominal jet radius can be set at 1 kiloparsec. A truly slow beam could have $v \approx 10^8$ cm sec^{-1}, which implies the particle density in the jet would have to be 1 cm^{-3} or greater, depending on ϵ. This is the worst case for mass loss, but over a source life of 10^8 years (which produces a 100-kiloparsec jet for $v = 10^8$ cm sec^{-1}) the total mass lost is 10^9 to 10^{10} solar masses. This number is large but perhaps not impossible, given that the total masses of the giant elliptical galaxies that produce radio sources can be as high as 10^{12} to 10^{13} solar masses. Because of the v^3 dependence in the energy balance equation, raising v a small amount above 10^8 cm sec^{-1} clearly reduces the mass loss and yet keeps the jet velocity definitely nonrelativistic. For $\epsilon = 0.01$ the total energy required over 10^8 years is $\approx 10^{61}$ erg, or $\sim 10^7 M_\odot c^2$, where $M_\odot$ is the solar mass. This is a large but not totally intimidating number; given that nuclear burning proceeds at an efficiency of ~ 1 percent, this is the energy generated by only 10^9 solar type stars over their lifetimes.

Compact Radio Jets and the Nuclear Engine

In addition to the large-scale jets discussed above, very small jets have been observed emanating from deep in the central portions of radio galaxies and QSO's (*18*). Typical sizes are of the order of 1 parsec. In almost all cases the jet is one-sided and appears to emanate from a bright core at the center of the parent optical object. In those cases where there is a large-scale one-sided jet also present, the compact jet lies on the same side as the large-scale feature. With a few important exceptions, the compact jets appear linear, but this may be due in part to the lack of detail currently available in radio maps of these tiny objects. Compact jets are very much less common than large-scale jets, and, because of their small population and small size, we have much less detailed information about them than about the large-scale jets.

The general inference is that energetic outflow is being observed just as it emerges from the central engine. The fact that compact one-sided jets are seen in galaxies and QSO's that also have large-scale double structure has been interpreted as evidence that the compact jets are moving at relativistic velocities (*18*). This interpretation rests upon the assumption that there are really two compact jets, each of which powers one side of the large double structure, and that the compact jets are directed almost exactly along the line of sight between the radio source and the earthbound observer. If this is the case and if the flow is relativistic, then the Doppler effect will enhance the observed radiation from the oncoming jet and suppress the radiation from the receding jet to the point where only one jet is seen.

This interpretation does encounter some difficulties, however. The fact that the jets are visible implies that they are inefficient, although this per se does not argue against relativistic motion. Perhaps the most serious objection arises from the following argument. The compact jet is presumed to be the innermost portion of the outflow which powers the rest of the extended radio source, including those that possess large-scale jets on the same side as the compact jet. I have argued above that there is convincing evidence that the large-scale jets are not in relativistic motion. If this is the case and if the compact jet both is relativistic and contains enough energy to power the entire radio source, then in the region between the end of the compact jet and the onset of the large-scale jet the flow must be decelerated from relativistic to nonrelativistic speeds. This explanation requires that most of the kinetic energy used to power the entire radio source must be dissipated in this small region. Even if a mechanism could be found to do this, earlier arguments about shock-wave randomization of relativistic flow would lead one to expect vast amounts of radiation to be emitted from such a dissipation region. Observations do not confirm this, for the interval between the compact jet and the large-scale jet is often characterized by decreased radio emission and is never seen as the brightest part of the entire source, as might be expected. In addition, there is no evidence for enhanced emission from this region at x-ray, optical, or infrared wavelengths. A final difficulty with relativistic motion for the compact jets arises from very recent observations made by the Multi Element Radio Link Interferometer (MERLIN) (*19*). These reveal compact radio jets that are strongly curved or bent through 180° or more, and the configurations cannot be reasonably explained by the use of precessing jets plus projection effects. If these jets are relativisitic and fuel-extended sources, their momentum density and rigidity must be very high; thus it is difficult to see how they can be bent without being destroyed.

There remains one phenomenon associated with compact jets that is very strong evidence for relativistic flow, and it is illustrated in Fig. 4. What is observed is a change in the jet structure over a period of time. The number of cases where this is seen is very small (<10), but this may be due to selection effects as very few compact jets have been monitored for such structural changes. These jets are almost exclusively seen in association with QSO's, and, if the red shifts of the QSO's are taken as an indicator of their distance, the progress of the outwardly moving knots of radio emission implies velocities in excess of c. In the case of 3C 273 (Fig. 4), this apparent velocity is about $\sim 10c$. More recent observations of the radio source 3C 345 show apparent velocities that are even greater (*20*). Relativistic motion of a compact jet nearly along the line of sight can account in a simple way for this phenomenon, due to Doppler effects (*18*).

However, although relativistic beaming can account for this phenomenon, it is not a unique solution. Several other explanations have been put forward (*21*), although in their present form all of them have difficulties of varying severity. These alternative ideas involve a variety of mechanisms, such as phase effects from reflected photons instead of actual motion of material, gravitational lenses and screens, or noncosmological interpretations of the red shift. Although relativistic beaming may in some sense be the most "natural" way to explain the superluminal effect, the problems of energy deposition described above for compact jets in general still remains. There is in addition a serious consistency question. If relativistic motion explains the superluminal effect, there must be a large number of unseen relativistic compact jets that are not pointed nearly along the line of sight. The energy carried by these must be deposited at some point when the jet is stopped, yet this large population of objects is not clearly identified. In addition, because compact jets associated with large-scale jets clearly have an energy deposition problem if they are relativistic, one is placed in the awkward position of explaining why some compact jets are relativistic and others are not.

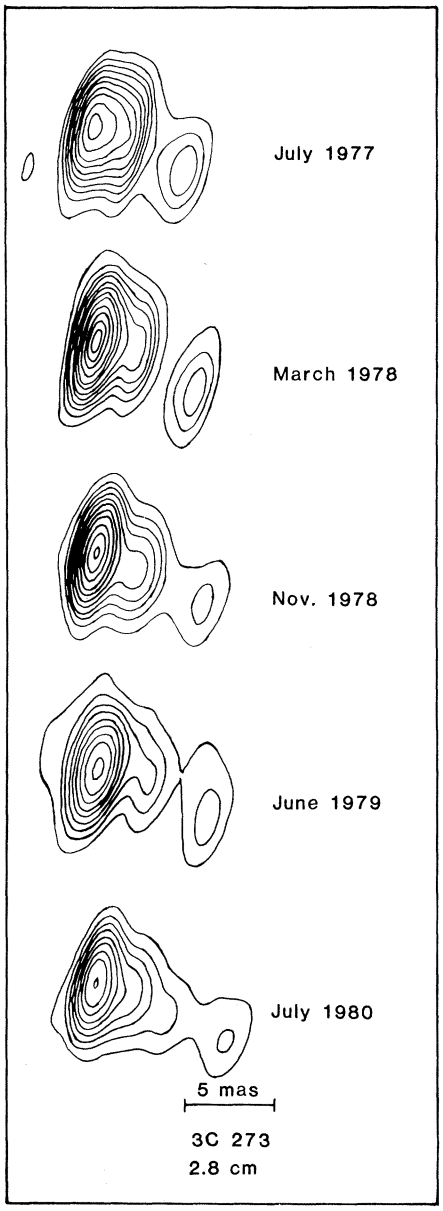

Fig. 4. Radio contour maps of the compact jet in the radio source 3C 273 made at different epochs; mas, milliarcseconds. [From (*18*)]

One of the questions of great interest about extended radio sources is the detailed nature of the central energy source. Although nonrelativistic motion of the jets will require modifications of the earlier models, no detailed calculations have yet been performed for a model that produces "slow" jets. It may well be that a very similar model based on nonrelativistic gas could be made to work, or a very different acceleration process may be required. Although compact jets are very close to this central energy source, most observations of them have provided little additional constraints as to its nature. Very high resolution maps such as the recent MERLIN results may change this in the near future.

One area where theoretical calculations have provided some extremely interesting results is in the modeling of the large-scale jets (*22*). Nonlinear numerical simulations of the hydrodynamics of supersonic but nonrelativistic jets have provided a wealth of detail to compare with observations. A key feature of these calculations is the role of the interaction of the jet with its environment. This interaction not only produces a bow shock but vortex sheets, surface instabilities, mixing layers, and internal shocks. These phenomena are precisely those required to drive the acceleration and entrainment processes needed to explain the observations.

Conclusion

The existence of jets or beams of outflowing material which provide a continuous supply of energy to the giant extragalactic radio sources is required by radiative lifetime arguments and is consistent with observational data. These same data also indicate that energy propagation in the jets is not highly efficient, and the morphology of large-scale jets argues strongly for nonrelativistic motion of the jets. If these jets are only mildly supersonic and dominated by nonrelativistic plasma, then the turbulent boundary layer that surrounds the jet may provide the required particle acceleration, magnetic-field amplification, and transport of metal-enriched gas far from the interstellar medium. Slow jets increase the total energy requirements for the source, but not beyond the limits of credibility.

Compact jets are also inefficient, and arguments can be made for their relativistic or nonrelativistic motion. At present there is no clear-cut resolution of this issue, but it is fair to say that a consistent picture could be constructed wherein all jets are nonrelativistic. Observations of jet phenomena in extragalactic radio sources seem to require modifications of earlier models for the central energy source, and, although these have yet to be done in detail, models of the interaction of jets with their environment supply encouraging agreement with observations.

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Criteria for Evidence of Chemical Carcinogenicity

Interdisciplinary Panel on Carcinogenicity

Criteria for assessing the evidence for the carcinogenicity of chemicals have been described in several documents including a 1977 report of the Subcommittee on Environmental Carcinogenesis of the National Cancer Advisory Board (NCAB) (*1*) and the preambles to the monograph series of the International Agency for Research on Cancer on the evaluation of the carcinogenic risk of chemicals to humans (*2*). The report of the subcommittee of the NCAB recommended that "The general criteria should be reviewed on a continuing basis and revised in the light of new knowledge."

The Interdisciplinary Panel on Chemical Carcinogenicity was convened by Philippe Shubik at the request of the American Industrial Health Council to reevaluate the criteria for assessing the evidence for the carcinogenicity of chemicals as a result of recent increases in the quantity of data and research in carcinogenesis (*3*). The panel met on 31 October and 1 November 1983 and 24 and 25 February 1984 in Washington, D.C. The report that follows is particularly concerned with those areas that have been most affected by advances in knowledge.

The panel expresses its concurrence with the philosophy that was well expressed by the NCAB subcommittee (*1*):

> The criteria that are described are general guidelines and not rigid, universal criteria. The complexity of the problem dictates that the evaluation of potential human hazards of a given agent must be individualized in terms of the chemical and metabolic aspects of that agent, its intended use(s), the data available at the time the decision must be made, and other factors pertinent to the case under consideration. Each case must be considered on its own and the criteria appropriate for one agent may not necessarily apply to another.

The panel also agreed that the generalized definitions and significance of benign and malignant neoplasm presented in the NCAB subcommittee's report were adequate for present purposes without modification (*4*).

Since 1977 numerous bioassays of chemicals have been reported from in vivo studies; many in vitro tests have been undertaken and new in vitro tests have been devised. As a result much new research on the mechanisms of action of chemical carcinogens has been reported and suggestions put forward for classifying carcinogens; the influence of biometrics has been prominent in the development of a variety of mathematical models for risk assessment; and there have been controversies about the overall quantification of risk from chemical carcinogens to the human population. These factors have been influential in determining the priorities for the present deliberations.

Evidence Derived from Human Studies

Clusters of cases of a specific type of cancer associated with a particular exposure suggest that certain chemicals or combinations of chemicals may be carcinogenic to man. This has been the basis for much of our current knowledge of occupational cancer occurrence. The problems that confront the epidemiologist in such situations include the reality of the excess cancer incidence, the difficulty of estimating exposure, and

The members of the panel were: Philippe Shubik, Green College, Oxford University, chairman; Arnold Brown, University of Wisconsin–Madison; Charles Brown, National Cancer Institute, Bethesda, Maryland; J. R. P. Cabral, International Agency for Research on Cancer; David Clayson, Bureau of Chemical Safety, Health Protection Branch, Health, and Welfare, Canada; Ian Higgins, University of Michigan; Wayne Levin, Hoffmann–La Roche, Inc.; Peter Magee, Fels Research Institute, Temple University, School of Medicine; Mortimer L. Mendelsohn, Lawrence Livermore National Laboratory; Robert A. Squire, Johns Hopkins University, School of Medicine; Bruce K. Bernard, Scientific Research Associates, Inc., rapporteur. Requests for reprints should be addressed to Dr. Philippe Shubik, Green College, Radcliffe Observatory, Oxford OX2 6HG, England.