EXTENDED RADIO SOURCES

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1. INTRODUCTION

The understanding of the nature of strong radio emission associated with galaxies and quasars has significantly increased in the last five years. A large contribution to this increase has been obtained from the arcsec and milli-arcsec mapping of radio sources which show remarkable features. Because of the recent, extremely good review articles concerning extended extragalactic radio sources (Miley 1980 and Willis 1978), I shall emphasize some new, mostly unpublished works, stemming from VLA observations. This is not to slight European experimental and theoretical work which have led in the formulation of our current thinking, but to try to bridge the inevitable communication gap caused by the Atlantic Ocean and ever higher airfares.

Perhaps, the most important advance in the last five years has been the success of the so-called beam-type models (e.g., Rees 1971, Blandford and Rees 1974) which explain many of the morphological features in radio sources and provide a theoretical framework which has led to a better understanding of the physics associated with galaxies and quasars. The acceptance of this model will be tacitly assumed in the following paper.

2. THE FOUR PARTS OF A RADIO SOURCE

Nearly all extended emission associated with extragalactic objects can be separated into four morphological parts--which also correspond to distinct physical processes occurring in the source. They are: the core, the jet, the hot spots and the diffuse emission. A somewhat simplified picture is given in Table 1 with a contour plot in Fig. 1 of NGC315 (Bridle et al. 1979) which display these features. The following discussion only touches the highlights of the radio emission, is not complete and is biased towards the beam models.

G. Setti, G. Spada, and A. W. Wolfendale (eds.), Origin of Cosmic Rays, 111–125.

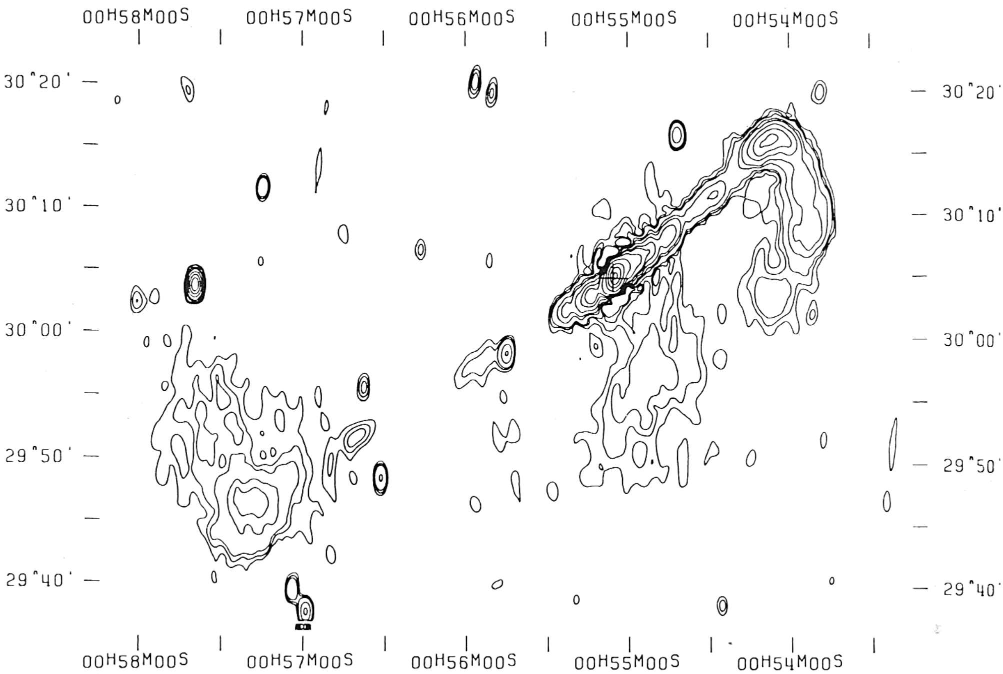

Figure 1. The radio source NGC315 at 610 MHz.

TABLE 1
The Four Parts of a Typical Radio Source

Morph. Part	Linear Size (kpc)	Spectral Index $S \sim \nu^{-\alpha}$	Equip. B Gauss	Percent Polar.	Role in Source
Core	< 0.01	0.0	10^{-3}	< 2	Energy Generation
Jet	2-1000	-0.6	10^{-5}	0-60	Energy Flow
Hot spot	5	-0.6	10^{-5}	15	Energy Conversion
Extended emission	50-1000	-0.9	$10^{-5.5}$	0-60	Energy loss and history

2.1 The Radio Core

Nearly all radio sources contain a small-diameter radio component, often less than 100pc in size, which is coincident with the optical nucleus of the galaxy. The radio strength is often variable over time-scales of months and the core is similar to "isolated" compact sources (Kellermann 1978). The spectral index of most cores is about 0.0 and the spectrum is consistent with self-absorption in some cases. Some cores do have steeper spectra and larger linear sizes but these are probably composed of a radio core and a small radio jet.

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The radio properties of cores can only be measured using VLBI techniques and these properties will be described by Pauliny-Toth in a separate article. The distinction of radio sources between those with extended emission and weak radio cores from those with dominant or isolated radio cores is becoming blurred and it is likely that we are dealing with the same class of sources. More on this later.

2.2 The Radio Jets

Many radio sources show linear features which emanate from one side or from opposite sides of the radio core. These jets, as the features are called, often extend hundreds of kiloparsecs and terminate into a hot spot in the radio lobes. The jets are most prominent in the lower luminosity sources; they tend to be one-sided; they often contain gaps, bends and wiggles; and they become wider further from the core. Although most luminous sources do not have prominent jets, the consensus is that beams do exist for these sources and that jets are seen only if some inefficiency in the beam has generated sufficient numbers of relativistic particles which then radiate. It is usually assumed that the visible jets fill the beams and that properties of the beam can be inferred from those of the jets.

The spectral index of most jets is about -0.6. Optical emission has also been seen coincident with the bright features of some radio jets (Butcher et al. 1980) and the spectral index defined from the radio to optical frequencies is also about -0.6. Linear polarization is also seen at optical frequencies and the radiation mechanism is probably synchrotron radiation. Recently x-ray emission has also been detected in jets associated with nearby galaxies.

Non-beam models which explain the existence of jets are not attractive. Plasmon models in which discrete blobs of relativistic and thermal matter are transported from the core to the lobes are not consistent with the generally continuous nature of the jets and the rapid supersonic flow necessary to keep the jets well-collimated. Similarly, the continuous jets do not support models in which the ejection of several large massive objects from the galaxy supply the majority of energy to the lobes. Clearly, the jet morphology is the crucial observational support for the beam-type models.

2.3 Hot Spots in Lobes

Extended radio sources often contain regions of size 5 kpc in the radio lobes which are significantly brighter than the surrounding lobe emission. The hot spots invariably lie near the termination of the radio jet or its extrapolation when one is visible. This morphology strongly suggests that the hot spot is generated by the disruption of the beam with the concomitant generation of relativistic particles. The spectral index of the hot spots is also similar to

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that of the jets. Occasionally there are several close hot spots in the lobes of luminous sources which complicates this simple interpretation somewhat.

There are several examples of optical emission associated with prominent hot spots in several radio sources (e.g., Simkin 1978, Saslow et al. 1978). As in the case of the jets, the optical/radio spectrum is about -0.6 and radiation at both frequencies is satisfactorily explained as synchrotron radiation.

2.4 Extended Emission

In addition to the hot spots, the radio lobes contain more diffuse emission. The spectral index of this emission is -0.8 and can be as steep at -1.3. In the extended emission the degree of polarization is large, intensity gradients are greatest at the edge of the lobes and the magnetic field structure is somewhat uniform. The morphology and placement of the extended emission with respect to the hot spots and the radio core vary widely.

2.5 The Overall Source Symmetry

The four parts of a typical radio source when taken as an entity do not form a precise linear system but usually show various symmetries and distortions. These have been illustrated by Miley (1980) and include "C"-shaped sources, "S"-shaped sources, curvature in radio jets, reflection symmetries through the core, etc.

These various morphologies are thought to be associated with the velocity and acceleration of the radio source in an external galactic medium, the dynamics and environment found in the galaxy as a whole, and the dynamics and environment of the pc-sized nuclear region. However, these effects do not appear to disrupt the basic energy flow mechanism very much but give the source a non-linear appearance.

3. RECENT OBSERVATIONS AND SPECULATIONS

The rate of production of high resolution radio maps from the VLA, Westerbork, Cambridge and Jodrell Bank, as well as accurate and detailed optical images, is now uncovering important details in radio galaxies. Models are becoming more realistic now that observational data can point out unambiguous features and physical conditions in the radio source.

It is too early to form firm models which fit the recent observations. Rather, I would like to briefly describe recent results and speculations associated with the latest observations (mostly from the VLA) which seem to be telling us something.

3.1 Compact Versus Extended Radio Sources

The separation of extragalactic radio sources into two distinct groups, compact and extended, is becoming blurred and I think one can safely state that 1) nearly all "isolated" compact sources have associated large-scale structure > 10 kpc in extent, and 2) nearly all extended sources have a radio core which may be identical to the so-called "isolated" compact sources. The difference may be only in the relative luminosity of these radio core and extended structure.

First, the recent observational evidence should be discussed. Using the VLA very sensitive and high resolution observations of "isolated" compact radio sources have shown that about half of them in a complete 6cm-survey sample contain extended emission of size about 10 arcsec. At 6cm the extended emission comprise about 5 percent of the total flux density. At 20 cm the percentage rises to about 15 percent. Some examples are given in Figure 2.

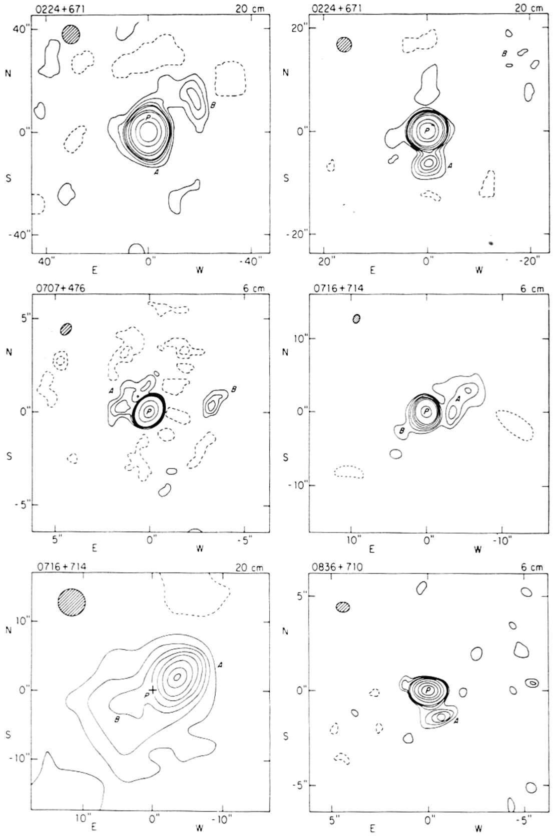

Figure 2. Examples of core-dominated radio sources. The lowest contours are at a level of 0.4% of the peak.

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These morphologies are similar to the "D2" class of Miley (1971) or the "C" class of Readhead et al. (1978) in which a faint steep-spectrum component is displaced from a flat-spectrum core. The source 3C273 is a good example. All of these core-dominated sources are luminous radio emitters and are usually identified with quasars or distant galaxies.

Based on maps of about 20 such sources, their radio properties are:

(1) The flux density is dominated by a flat-spectrum core which is coincident with a galaxy.
(2) One or more secondary components are displaced about 10 kpc from the core. These components have spectral indices of about -0.8 and are about 5 kpc in size.
(3) More diffuse emission is usually present in a non-descript morphology and position with respect to the other components. The spectrum of this component is also steep.

This overall morphology does not fit in with the usual structure of extended radio sources. Because of the extreme luminosity in the core the normal collimating and transport mechanisms may not be operating with the result of a smaller, less symmetric radio source.

Recent work on relativistic flow in jets by Scheuer and Readhead (1978) and Blandford and Königl (1978) may provide an explanation of the core-dominated morphologies in the framework of the more typical radio structure. The model suggests that the radiation from a region near the core may be doppler-enhanced if the flow from the core is relativistic and in the direction of the observer. For a flow with $\gamma = 7$ within 8 deg of the line of sight, an enhancement of a factor 500 can be obtained. Any associated extended structure, presumably unaffected by relativistic flow, would be faint compared with the core. Because the source would be viewed nearly along its radio axis, any non-linearities in the source structure would be magnified. Thus, the secondary components seen may be lobe hot spots and the more extended emission would then be the larger-scale lobe emission. A source like Cygnus A, when viewed along the line of sight with a core enhancement of 500, could look similar to the sources shown in Figure 2.

More detailed data are needed to test the above hypothesis. Verification of this model will be an important test in determining if relativistic flow velocities do occur in the inner parts of radio jet in luminous sources.

3.2 The Collimation of Radio Jets

By now the properties of radio jets are well-known. Some examples of sources with these linear features are shown in Figure 1 and 3. Some of the general properties are:

(1) The jets are usually asymmetric in intensity.

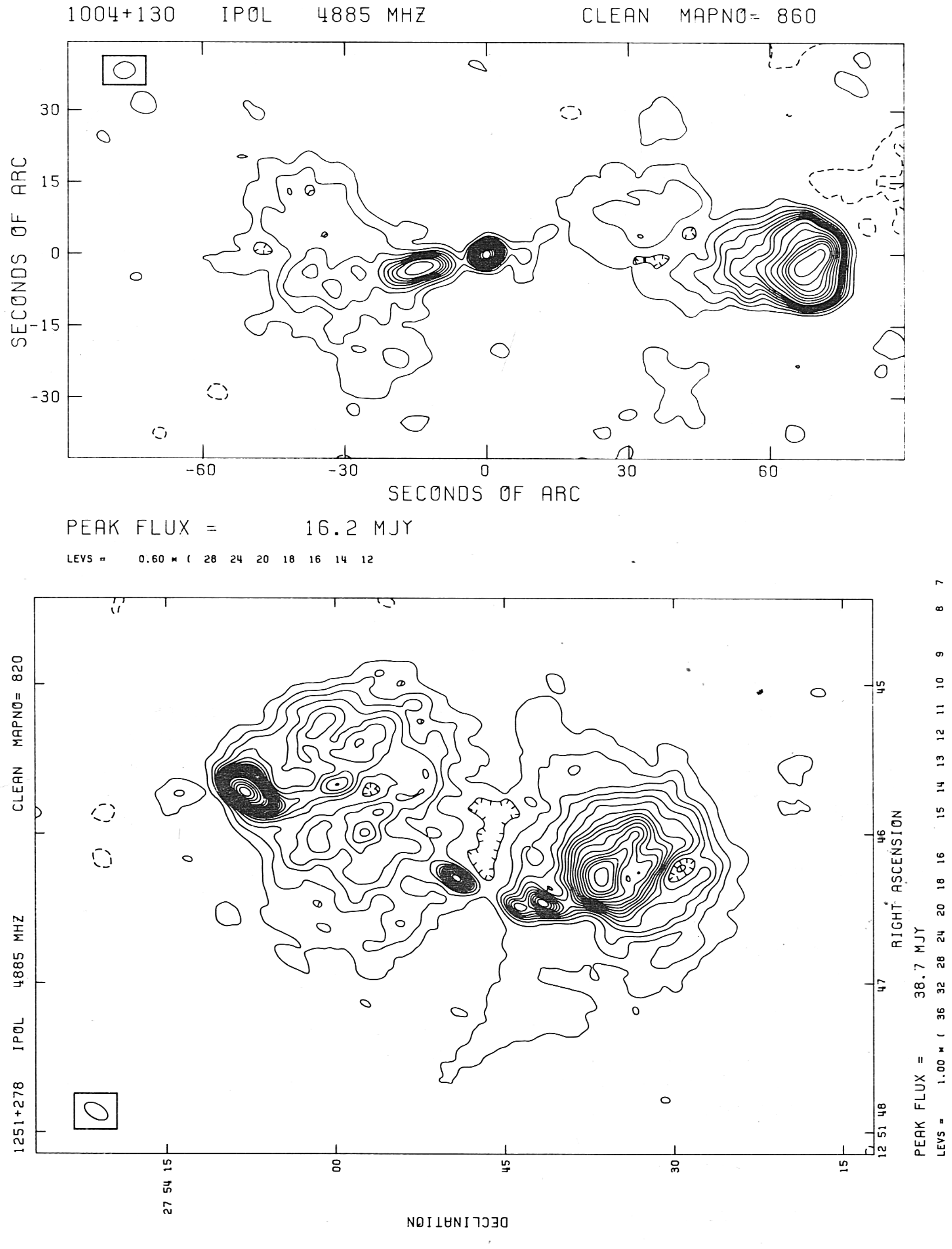

Figure 3. Radio sources with jets.
(a) 1004+130 at 4.9 GHz
(b) 1251+278 (3C277.3) at 4.9 GHz

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(2) Often, there are gaps in the jet and most jets do not start until several kpc from the radio core.
(3) There are wiggles, bends and kinks in the jets. Often these features in the jets show a reflective symmetry with respect to the core.
(4) Jets associated with low luminosity sources are generally prominent and have average opening angles of about 10 deg. Jets are not seen often in the higher luminosity sources and when visible have opening angles less than about 3 deg.
(5) The magnetic field direction in the inner region of the more prominent jet is oriented parallel to the jet axis. This orientation flips to perpendicular to the jet axis, the distance from the core where this flip occurs varies directly with the source luminosity. For the luminous sources, the magnetic field remains parallel to the jet axis. The less dominant jet, if visible, has its magnetic field always perpendicular to the jet axis (Fomalont et al. 1980).
(6) Recent dual-frequency observations of the linear polarization in 3C449 (Perley et al. 1979) and NGC6251 (Perley et al. 1980) suggest the presence of significant thermal material.
(7) The opening angle of the jets is not constant but generally decreases with distance from the core.

From point (7) above we see it is apparent that the jets do not expand uniformly as would be expected by a freely expanding supersonic flow. The departures can provide clues to changes in the pressure equilibrium (if the flow is confined) or changes in the effective equation of state (if the flow is free). Recent work by Chan and Henriksen (1980) and Bridle et al. (1980) have investigated the collimation properties in several jets with interesting conclusions.

They adopted the dynamics of a supersonic, but non-relativistic, magnetized beam. They derived a self-similar solution (azimuthally symmetric, radially scale-independent, arbitrary axial dependence) for the magnetic field, flow velocity, specific angular momentum and effective temperature. They also assumed that the jet was heavy; i.e., the relativistic particle energy is only a small fraction of the total energy. This latter assumption seems valid in the light of the depolarization data associated with jets and the requirement of reacceleration in the jets to keep them visible. Most reacceleration mechanisms invoke significant amounts of thermal matter.

One conclusion they draw is that if the energy in the circumferential magnetic field is more than one percent of the kinetic energy in the flow down the jet (somewhat less than the equipartition value one would calculate in the normal way), significant pinching of the beam will occur and radial oscillations would be present. Such oscillations are not observed on the necessary scale and thus rule out the dominance of circumferential magnetic fields in non-relativistic jets (see Fig. 4, curve a and b).

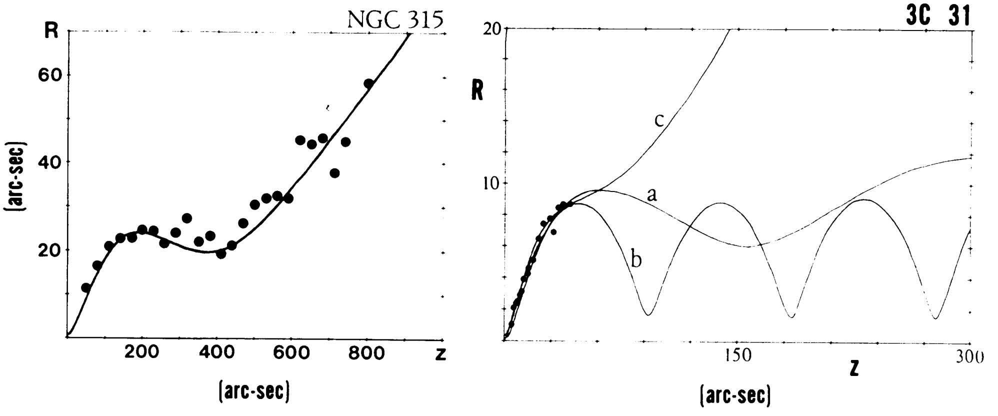

Figure 4. Fits to collimation of NGC315 and 3C31 jets. The dots show the width R of the jet with distance Z from the radio core. The various models are described in the text.

With the x-ray detection of extended (100 kpc), hot (> 10^7 K) gaseous haloes around M87 and Cygnus A (Fabricant et al. 1978, 1979; Fabbiano et al. 1979) it is attractive to consider the possibility that jets in low-luminosity sources are confined by external pressure. A confining atmosphere with a single pressure scale cannot, however, produce decreasing expansion rates such as those observed in most jets. Such a decrease can be effected by a two-component atmosphere. First, the beam is collimated by a dense "nuclear" atmosphere whose pressure decreases rapidly. After some distance this nuclear atmosphere is supplanted by one with a more slowly decreasing pressure. Such a model fit to 3C31 is shown in Figure 4, curve (c); a more impressive fit to the north-west jet in NGC315 is shown in Figure 4. The parameters for this fit were:

Beam radius at sonic point	0.75	arcsec
Scale hight of nuclear atmosphere	5.0	arcsec
Power law of nuclear atmosphere	4.0	
Scale height of second atmosphere	140.0	arcsec
Power law of second atmosphere	2.5	
Height where two pressures are equal	52.0	arcsec
Density where two pressures are equal	1000	cm^{-3} T^{-1}

The decrease in the expansion rate of the jet in the region where the two components of the external pressure are about equal can be explained in the following way. Initially, the pressure balance between the nuclear atmosphere and the relativistic particles

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sets up a supersonic collimated jet in which the thermal matter inertia keeps the jet collimated with a relatively constant opening angle. This opening angle depends on the rate of decrease of the pressure which varies as Z^{-4} in the model for NGC315, and the internal temperature decreases down the jet. When the outer atmosphere, which decreases as $Z^{-2.5}$ becomes dominant, the external pressure decreases slower than the thermal pressure. The jet width then contracts until the thermal gas heats sufficiently to restore an inertially collimated flow at a new expansion rate. The assumption of this type of galactic atmosphere is _ad hoc_ but at least one can demonstrate that the collimation properties of low luminosity jets can be reproduced from simple pressure confinement with little or no magnetic confinement. The halo densities implied in this model are also reasonable.

The relation between expansion rates and magnetic structure may be different in the more radio luminous jets (Perley _et al_. 1980, Potash and Wardle 1979). These jets may be highly relativistic and the magnetic field direction is parallel to the jet axis.

3.3 Precession of Jet Axes

The evidence is accumulating that the ejection of energy which operates in the galaxy nucleus precesses or swings significantly. Such a precession produces morphologies in sources with reflective symmetries. The source NGC315 in Figure 1 is a good example of the "S"-shaped structures one obtains. In this and virtually all other sources the jet points to or blends into a hot spot at one edge of the radio lobe. The remaining lobe structure, transverse to the jet axis, is then populated with relativistic particles deposited when the jet pointed in that direction. The length of this transverse lobe region depends on the rate of precession of the jet, the radiating lifetime of the particles, the reacceleration mechanism operating in the lobes and the effective speed of the end of the jet (relativistic time delay effects may be important).

A morphology suggestive of more extreme precession is shown in Figure 5 for the sources 3C315 and NGC326 (Northover 1976, Ekers _et al_. 1978). These maps were recently made at the VLA. Here the outer lobes are more extended and both show the reflective symmetry necessary for precession. The jet in NGC326 points to the hot spots at the edge of each lobe as expected. Recent high resolution observations at the VLA show that 3C315 does have a short radio jet which also points to a warm spot near the edge of the radio lobe. Distortion of the lobes by orbital acceleration (Blandford and Icke 1978) as in the outer parts of 3C31 and 3C449 cannot explain the morphology in 3C315 when the jet direction is considered.

It seems significant that both radio sources are associated with a close pair of galaxies, indicated by the crosses in Figure 5. Such close interaction could account for more rapid precession than normal (Rees 1978).

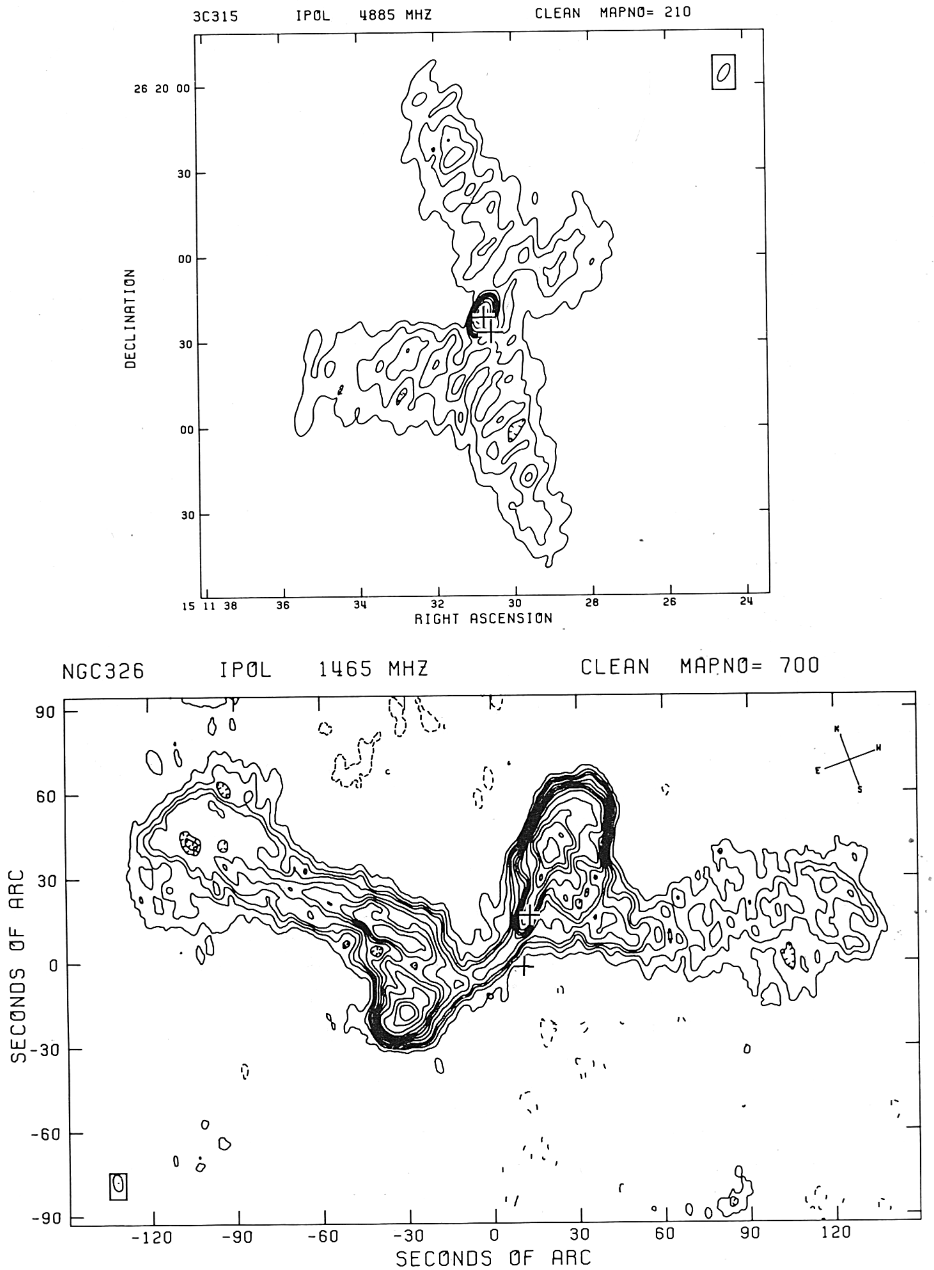

Figure 5. Two sources with rotational symmetry.
(a) 3C315 at 4.9 GHz (b) NGC326 at 1.5 GHz
The crosses show the galaxies near the core.

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3.4 Freaks

Quite often, the study of freak morphologies can better contribute to an understanding of some aspects of radio source evolution. The following two sources may be of interest in this regard.

The source 3C293 is the relatively close, 14-mag galaxy, VV5-33-12 with a peculiar optical structure (Argue et al. 1978). The minor axis of the light distribution is in position angle 60 deg but the galaxy shows several knots on the blue Palomar Sky Survey. The overall radio structure with five arcsec resolution at 20cm is shown in Figure 6 (Bridle and Fomalont 1980). The dashed outline shows the approximate edge of the optical galaxy. There is a dominant core which is steep in spectrum and about 2 arcsec extended in position angle 90 deg. An 0.2 arcsec resolution map at 2cm shows that the "core" is composed of three components and the galaxy nuclei is between two of these components. This is, obviously, not a true radio core. A jet emanates from the core, first in position angle 90 deg, then bends to position angle 180 deg, then bends back to a position angle of about 110 deg before terminating in a radio lobe. Faint emission to the south-west of the core does exist and is better seen on a lower resolution map which is not included here. Thus, 3C293 has a, more or less, typical triple radio structure although the core is very dominant.

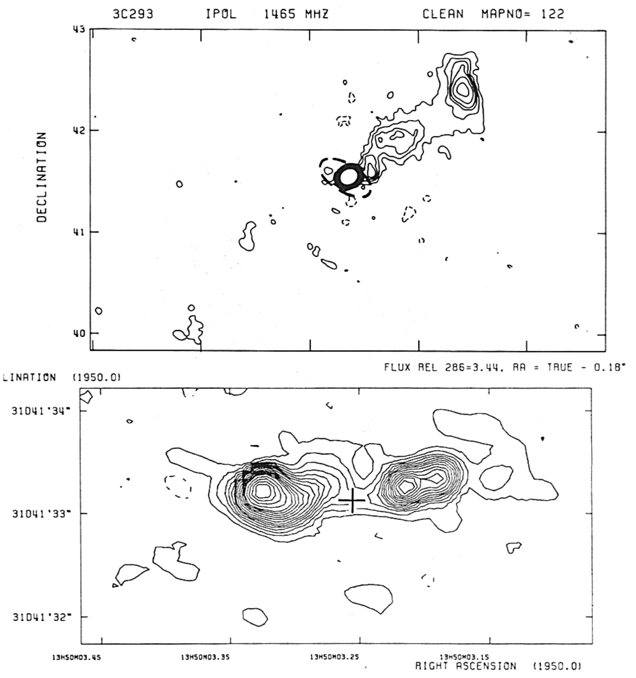

Figure 6. The radio source 3C293.
(a) 5" resolution at 1.5 GHz with galaxy outlined
(b) 0".2 resolution at 15 GHz with galaxy nucleus as +

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The segmented appearance of the jet is extremely curious and its cause can only be speculated. Precession of the energy source of the jet cannot produce such a morphology. Orbital acceleration of the nuclear engine as it rotates rapidly around another object could produce a flow with the appearance of the north-west jet (Blandford and Icke 1978), but the south-west lobe emission is in the wrong place for this model.

The correlation found by Palimaka et al. (1978) and Guthrie (1978) that the radio axis tends to align with the minor axis of the galaxy suggests that radio jets try to find a path of least resistance out of the galaxy. If elliptical galaxies are oblate rotators, then there may also be a dynamic influence in this minor axis-radio axis correlation. Thus, one might speculate that the jet in 3C293 has taken the path of least resistance and has deflected on two occasions to avoid high density regions. Because of the knotty appearance of the galaxy, such a devious route might be necessary.

The lack of a true, flat-spectrum, radio core in this source is also peculiar. The role of the two arcsec feature near the nucleus is also strange. In some ways this component resembles the nuclear emission associated with 3C236 (Fomalont et al. 1979) which also has a majority of emission in a steep spectrum source near the nucleus of the galaxy.

Fornax A, identified with NGC1316, has recently been observed optically (Schweizer 1980), the large-scale radio emission has been accurately mapped (Goss et al. 1980) and a small radio jet has been detected (Fomalont and Geldzahler 1980). The radio maps are shown in Figure 7. The structure near the nucleus contains three radio components. A core, coincident with the nucleus, with again a relatively steep spectral index of -0.5. A radio jet with spectral index -0.5 emanates from both sides of the core for about 1 kpc in a position angle of about 100 deg. The jet then deflects to an angle of about 145 deg, steepens to a spectral index of -1.2, which is unusual, and disappears after about 2 kpc. This part of the jet points to the outer edges of both radio lobes, but no significant hot spots are apparent. It is suggested that the energy flow in the jet has been recently terminated.

The optical studies of the galaxy show that dust and ionized gas appear to be rotating quickly and their axes are inclined to that of the nuclear stellar system by about 90 deg. It appears that a significant amount of gas is now infalling into the nuclear region and has interrupted energy flow to the outer lobes. Such infall of gas or another galaxy has been suggested as the fueling for strong radio emission (Shklovski 1962, Rees 1978). If so, NGC1316, the third closest strong radio source, is worth detailed study to understand this possible fueling mechanism of radio sources.

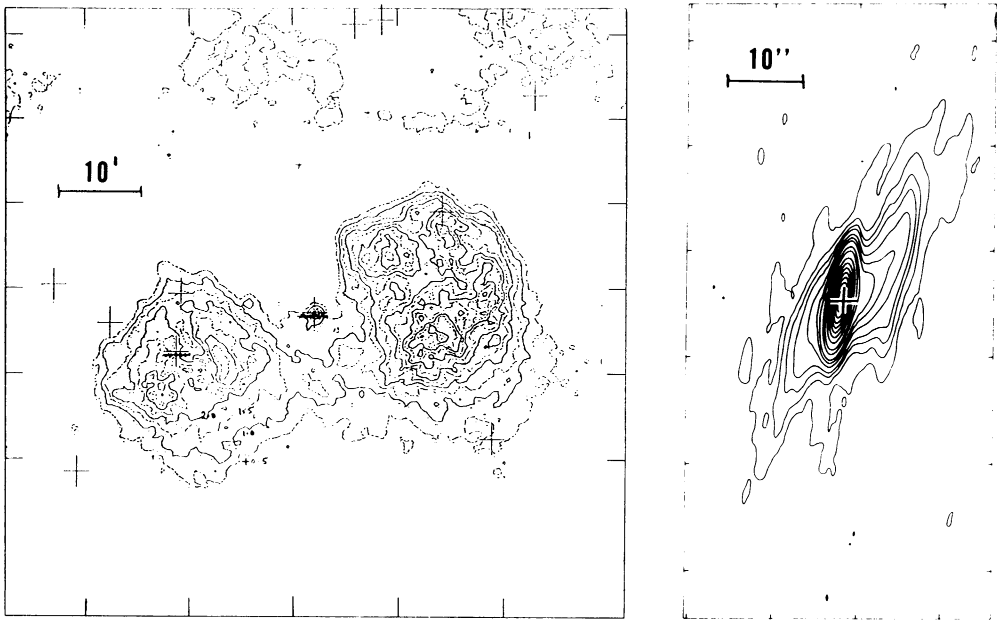

Figure 7. The radio source Fornax A
(a) 40" resolution at 1.4 GHz
(b) 3" resolution of central region at 4.9 GHz

4. SUMMARY

It may not be too strong of a statement that for the first time astronomers are getting to the heart of the physical processes which determine radio sources. Continued high-resolution mapping of the details in the sources and more accurate modeling of their physical conditions promise a more complete understanding of one of the most energetic phenomenon in the universe.

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