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DUMBBELL GALAXIES AND PRECESSING RADIO JETS

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Received 12 August 1981; revised 18 January 1982

ABSTRACT

We have compiled a catalog of ~100 close double elliptical galaxies which are radio sources. Many of these are dumbbell galaxies, i.e., two nearly equally bright elliptical galaxies in a common envelope. We argue that the close proximity of the galaxies (~10–30 kpc) will dynamically affect the radio jet through gravitational interactions with its confining gas cloud. The double galaxies may be either in highly eccentric (or unbound) orbits or in circular orbits. In the first case, an impulsive interaction can lead to inversion-symmetric jets, such as in NGC 326. In the second case, the continuous tidal interaction can produce periodic mirror-symmetric wiggles in the radio jet. For high-velocity circular orbits, e.g., 3C 465, a wide-angle tail will occur, even though the center of mass of the dumbbell galaxy is at rest in the cluster. Our picture contributes to the growing evidence that the large-scale galactic gas distribution is equally as important as the central engine for determining jet properties, such as direction and collimation. We stress the current uncertainty in the nature of the underlying gravitational potential of these systems. Progress can be made by a careful program of observations using a morphological scheme we outline. We present the results of new optical observations on two prototypes for our scheme: NGC 326 and NGC 750/751.

I. INTRODUCTION

It is by now widely accepted that the double-lobe radio sources are supplied with energy and momentum by twin jets originating deep in galactic nuclei (see, e.g., Rees 1981). In the last five years the production of high-resolution radio maps has resulted in the detection of these jets in many radio sources. Although some jets are straight, a large number exhibit complex bending on a scale of kiloparsecs. Early on (Harris 1974), it was recognized that the morphology of distorted extended radio sources could be broadly classified as either mirror symmetric (C-shapes) or inversion symmetric (Z-shape).

This conceptual division (see Miley 1980 for a recent discussion) has led to the dynamical interpretation that C shapes represent translational motion of the jet source (Miley *et al.* 1972), while Z shapes are caused by precession of the jet (Miley 1976). The translational motion is either motion of the parent galaxy through a cluster, with ram pressure of the intracluster gas sweeping back the jets (e.g., Begelman, Rees, and Blandford 1979; Jones and Owen 1979), or orbital deflection of a galaxy by a nearby galaxy, with the jets continuing in a ballistic trajectory (e.g., 3C 31—Blandford and Icke 1978). Jet precession is less well understood. Most discussions envision the axis of the central engine (generally assumed to be a black hole of $10^8 M_\odot$, radius 10^{-5} pc, see, e.g., Rees 1981) to precess or realign. This can be caused by accretion of new gas with a different angular momentum vector from the central engine (Rees 1978) or by the induced geodetic precession of a nearby black hole from a freshly accreted galaxy (Begelman, Blandford, and Rees 1980).

Our purpose in this paper is to suggest that a subclass of the Z-shaped sources have shapes produced by effects on large (galactic) scales compared with the central engine. This subclass is defined by those sources whose underlying galaxies have a "dumbbell" (db) or "multiple nuclei" optical morphology. That a number of strong radio sources (3C 40, 3C 75, 3C 278, 3C 310, 3C 338, 3C 433) were associated with db galaxies was first pointed out by Harris and Roberts (1960).

We present new optical observations which indicate that in one well studied inversion-symmetric source, NGC 326 (Ekers *et al.* 1978), there are two galaxies passing at a projected distance of ~10 kpc and that the gravitational coupling of the nonradio galaxy on the radio galaxy's atmosphere may be the mechanism which has realigned the jet direction. We point out that about a dozen radio sources with Z or X symmetry are associated with db galaxies and suggest further observational tests of our hypothesis. If correct, our interpretation implies that some large-scale jet properties (direction, collimation, etc.) of double radio sources are telling us more about properties of the gas distribution in galaxies and less about the central engine than heretofore supposed.

II. TAXONOMY OF DG'S

a) New Optical Classification for Double Elliptical-like Galaxies

Because of the inconsistencies in the literature for classifying the optical morphology of these radio galaxies, we present here a clear and concise classification scheme. This scheme is basically a slight modification of the Yerkes system as described by Morgan, Kayser, and

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White (1975, hereafter referred to as MKW).

Just as is the case with double stars, the name double galaxy (hereafter referred to as DG)* tells us nothing about the physical association of the components of the apparent system. It is simply a morphological classification meaning that two galaxy images are sufficiently close together as to be considered as related by the classifier. For the purposes of classification we will define close to mean that some visually detectable isophote encloses both galaxy images (for our sample, this turns out to imply projected separations of 5–30 kpc). Again, by analogy to double stars, it is permissible to give a morphological (in the stellar case, spectral) classification of the individual components of the double galaxy. This is what Mathews, Morgan, and Schmidt (1964, hereafter referred to as MMS) did in classifying optically double radio galaxies, although without an explicit notation.

In order to put this classification in a more concise form the following notation is suggested:

$$\mathrm{db}[\mathrm{ff}_1\mathrm{IC}_1, \mathrm{ff}_2\mathrm{IC}_2]$$

or

$$\mathrm{ud}[\mathrm{ff}_1\mathrm{IC}_1, \mathrm{ff}_2\mathrm{IC}_2],$$

where

ff_1 = form family for one component,

IC_1 = inclination class for one component,

ff_2 = form family for other component,

IC_2 = inclination class for other component,

and where db (dumbbell) is used if the difference in magnitudes of the two galaxies is < 1 and ud (unequal double) if $\Delta m > 1$. The form family gives the type of galaxy (E, D), while the inclination class denotes the apparent axial ratio of the galaxy. For example, in this scheme NGC 7236-7 (3C 442, see MMS) would be classified as

$$\mathrm{db}[\mathrm{D1}, \mathrm{D3}].$$

To some extent, this classification method reduces the dependence of morphological type on plate material (for a discussion of this problem see Wirth and Gallagher 1980).

Examination of detailed isophotes of a number of db systems leads us to one further classification: the deviation of the isophotes of the individual galaxies from pure ellipticality. (See, for example, NGC 750/1, Fig. 1.) We propose that the db notation be followed by a numerical ranking, on a scale from 1 to 7, of the extent of nonellipticalness, e.g., NGC 750/1 would be db7, while NGC 326 (Fig. 3) defines the dbl class. For ease in discussion, we will call this parameter the T class. We will elaborate on this classification scheme in a future paper.

*Other names in the literature are also used: multiple nuclei, cD plus satellites, compact cluster of galaxies, binary ellipticals, ellipticals in common envelope, contact elliptical galaxies.

b) Radio Structure

The radio morphology of these galaxies may be broadly classed as mirror symmetric or inversion symmetric. As was stated in Sec. I, these symmetries are denoted by C and Z. There exists a subclass of Z symmetry that we shall call X shape, in which it appears there are two separate jet structures emerging from the galaxtic nucleus in the form of an X. Finally, we note that these symmetries may be combined, e.g., CZ, etc.

Figure 2 is a graphical summary of the taxonomy of DG's.

III. GASEOUS HALOS

In previous discussions of radio-jet morphology, most attention has been placed on the intracluster medium, since the radio lobe structures occur on scales ($\sim$100–1000 kpc) comparable to or larger than the source galaxy ($\sim$10–100 kpc). However, this emphasis must be shifted to the gas retained by the individual galaxies in the case of DG radio sources, since the galaxies are separated by a distance comparable to the optical image of each galaxy.

Evidence has been accumulating that at least some elliptical galaxies can have significant amounts ($\sim 10^9 M_\odot$) of hot ($\sim 10^7$–10^8 K) gas bound to them (see, e.g., Fabian, Schwarz, and Forman 1980), either by dark massive halos or pressure confinement from the intracluster medium. Previous studies (see references in Fabian *et al.* 1980) indicate that usually much less ($< 10^9 M_\odot$) cold gas exists. In some central cluster galaxies (like M87), these gaseous halos may even extend to hundreds of kiloparsecs (Fabricant, Lecar, and Gorenstein 1980).

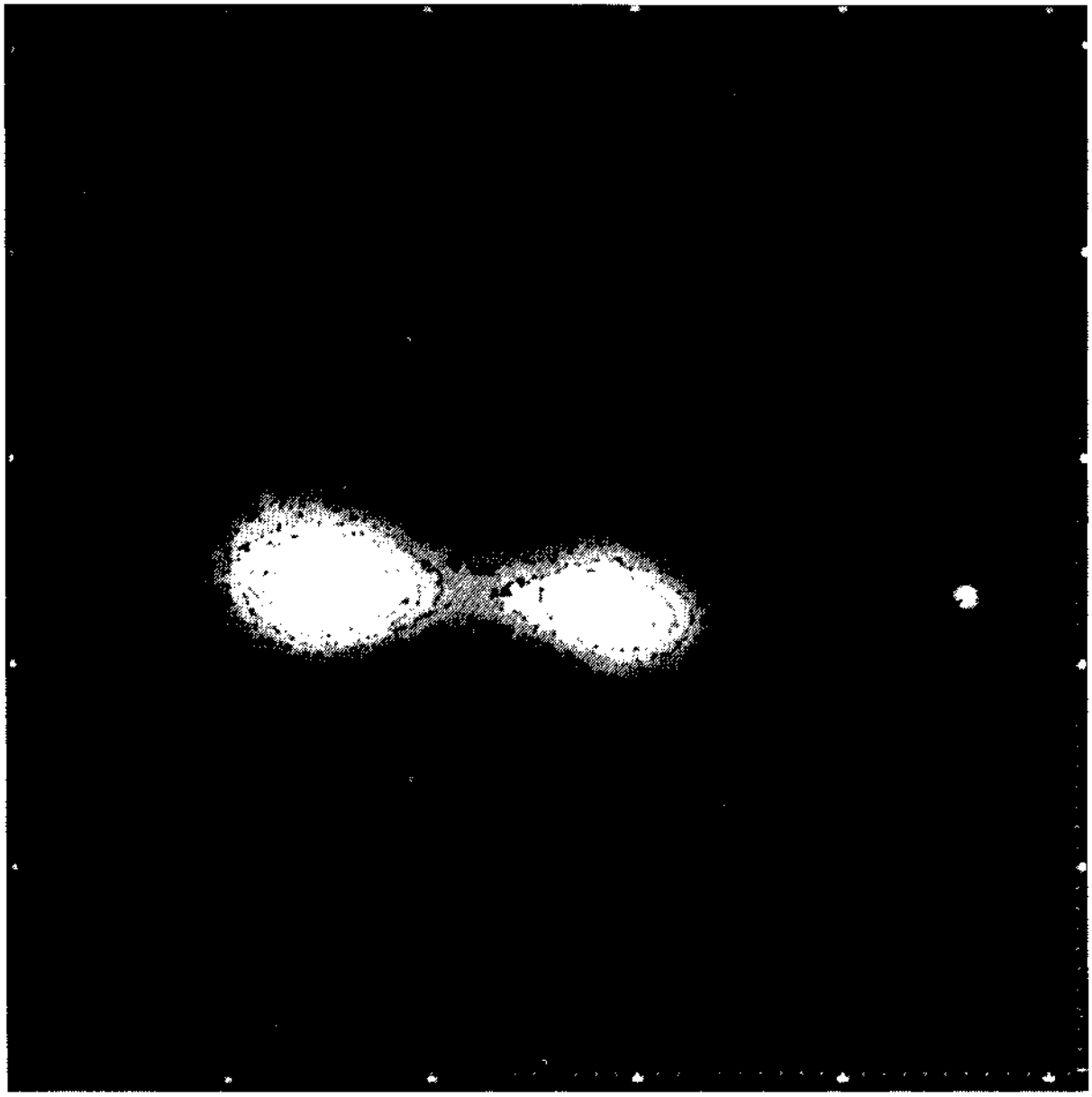
An important property of gaseous halos is that they may confine and collimate jets. A study of 3C 31 (Bridle *et al.* 1980) indicates that a hot confining halo can explain the apparent decrease in the opening angle of the jets on scales of $\sim$10 kpc. More recently, Henriksen, Vallée, and Bridle (1981) have proposed a model for Z-shaped jets in *isolated* galaxies. They note that if a gaseous halo of the type just described exists, then a jet whose initial direction is not along the minor axis of the potential well will be bent by the pressure gradients of the gaseous halo. The sense of the bending will be to form a reflection-symmetry (Z) jet.

In fact, the very existence of jets may be caused by this gaseous halo. A recent model (Sparke and Shu 1980) proposes that the lower angular momentum gas in ellipticals may cause narrow low-density channels along the global angular momentum vector of the galactic gas. For lower-luminosity radio galaxies, these channels would be what determined the jet direction, not the central engine (e.g., black hole axis).

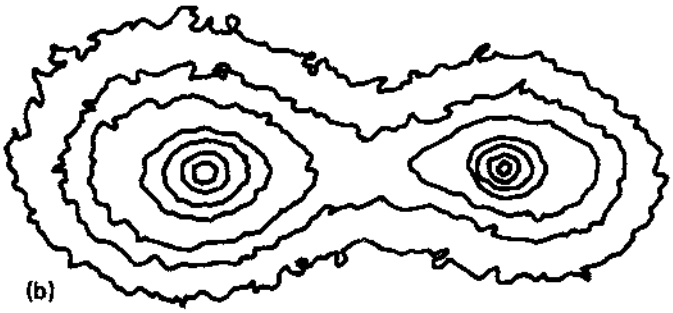
Given the seemingly important character of the gaseous halos for radio-jet morphology, it would seem that sending another equally massive galaxy to within 10 kpc of a radio galaxy (i.e., a db-form galaxy) would strongly influence the jet properties.

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(a)



(b)

FIG. 1. (a) Isophotal map and image of NGC 750/1 derived from a 14-min *B*-bandpass exposure using KPNO 2.1-m telescope and video camera. Isophotes were produced using the IPPS at KPNO. (b) Isophotes for NGC 750/1 from same data, produced by the GIPSY at Groningen University. Note: both are linear instrumental intensity units.

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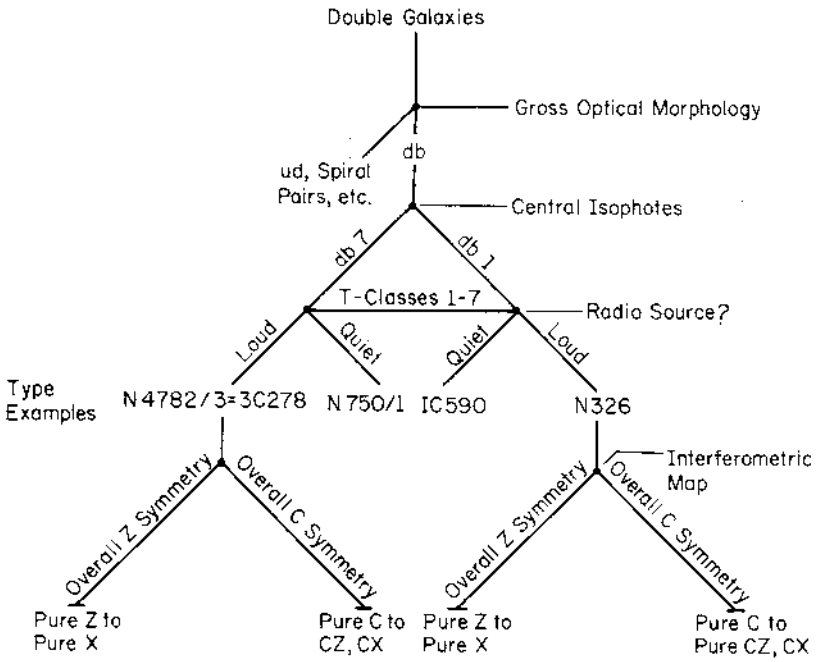


FIG. 2. Tree diagram for new classification scheme for double galaxies (see text for detailed description).

IV. THE PHYSICAL NATURE OF DG's

a) The Nature of the Potential

As stated in Sec. III a, the DG classification is morphological. We now examine what observations can reveal about the physical interaction between the galaxies. In some cases the DG is the result of projection. However, many DG's are the brightest galaxies in cluster cores. (Of our highly biased sample of ~70 bright pairs in the Appendix, $\sim\frac{1}{2}$ are in Abell clusters.) Rood and Leir (1979) have analyzed the probability of chance superposition for the db's which dominate Abell cluster cores. They conclude that the probability of such an occurence is $\lesssim 10^{-3}$. Thus in many cases the galaxies in cluster core DG's are close enough to affect each other. This argument is less valid in group or field DG's.

The nature of the physical interaction depends crucially on the shape of the gravitational potential in which the stars and gas of the galaxies move. The simplest case would be if the potential were determined self-consistently by the mass of the stars which give the visible light from the galaxies. However, there is evidence (see, e.g., Faber and Gallagher 1979; Fabricant *et al.* 1980) that galaxies may possess massive dark envelopes on scales much larger (~100 kpc) than their optically visible extent. If the elliptical galaxies in our DG's have dark halos, these halos will have largely overlapped. Even more extreme, the DG's which are brightest cluster members may be bound in the center of the cluster potential, the shape of which could be largely determined by the cluster dark matter (Blandford and Smarr 1981), with the galaxies acting as test particles in the external potential. Determining whether the gravitational potential is generated by visible or invisible matter is all important, both to the jet dynamics and to the distortions of the galaxies. For instance, the differential gravitational force across the galaxy can range from tidal to compressive depending on the potential (Blandford and Smarr 1981).

This fundamental uncertainty in the gravitational potential makes it very difficult to interpret theoretically the simplest observational facts about DG's. Questions one needs to answer to form a model are:

(1) What are the orbits of the galaxies (circular or highly eccentric)?
(2) Correspondingly, are the galaxies interacting continuously or impulsively?
(3) Is a lack of tidal distortion of the isophotes an idication that the galaxies are not physically close?

We attack the ambiguity by two lines of research. The first is to assume various potentials and derive consequences. The second is to make new observations on a large class of DG's and morphologically sort them into classes. We hope this will then provide a data base from which an answer as to the nature of the potential can be derived.

b) Impulsive Interaction and Precessing Jets

We briefly show how one can follow the first method to derive a picture explaining why some DG's might cause inversion-symmetric radio jets. We only expect such jets if the DG represents the aftermath of a transient impulsive encounter. (Of course, half of DG's with

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highly eccentric orbits will represent galaxies still approaching each other before any jet interaction can have taken place.) We offer two mechanisms which could explain why the impulsive encounter would torque the jet. The first involves the direct torque of the rotating confining gas cloud. The second involves the change in the stellar distribution in the radio galaxy. In both cases we assume (1) the gravitational potential is determined by the stellar distribution in the galaxy, and (2) that the jet direction is determined by the interstellar medium gas within the galaxy.

Let a jet-confining gas cloud of radius R and mass M_c attached to the radio galaxy (mass m) be impulsively torqued by the other member (mass M) of the DG during a close encounter. Let the separation of the galaxies be r and the orbital velocity be V_o. The cloud will have some ellipticity ϵ, which (for elliptical galaxies) is unrelated to its velocity of rotation V_r (Illingworth 1972). The torque integrated over time of closest passage

$$(GMR^2r^{-3})(M_c\epsilon)(rV_o^{-1})$$

will be set equal to the change in angular momentum of the cloud $\theta(M_cR^2)(R^{-1}V_r)$, where θ is the angle the rotation axis is moved through. This equality yields

$$\theta \sim \epsilon\left(\frac{R}{r}\right)\left(\frac{GM}{r}\right)\left(\frac{1}{V_oV_r}\right).$$

But

$$\frac{GM}{r} = \left(\frac{Gm}{r}\right)\left(\frac{M}{m}\right) \sim V_o^2\left(\frac{M}{m}\right),$$

so

$$\theta \sim \epsilon\left(\frac{R}{r}\right)\left(\frac{V_o}{V_r}\right)\left(\frac{M}{m}\right).$$

For a typical DG we have $R \sim r/2$ and $M \sim m$. Elliptical galaxies are known to rotate slowly ($V_r \lesssim 100$ km/s), while our db's have $\Delta V_{\rm obs} \sim V_o \sim 300$–$1200$ km/s, thus $V_o/V_r \sim 3$–12. This means $\theta \sim (1.5$–$6)\epsilon$, which can be a fraction of a radian for reasonable values of ϵ. Once moved, the gas will slowly move back as different parts of the gas halo precess at different rates in the galaxies' quadrupole gravitational potential (see, e.g., Tubbs 1980 or Gunn 1979). Thus, on a long time scale (compared to encounter time), the jet will be torqued back into alignment with the stellar gravitational quadrupole-moment principal axis set by ϵ.

The second mechanism requires the stellar distribution of the radio galaxy to change as a result of the tidal forces acting during close passage of the two galaxies. Assume that each of the two elliptical galaxies can be represented by a triaxial ellipsoid. The confining gas cloud will have settled into gravitational potential of the radio galaxy with its minor axis presumably coinciding with the minor axis of the stellar distribution (e.g., Kotanyi and Ekers 1979; Tohline *et al.* 1982). The axis has some fixed direction in absolute space, which will coincide with the jet axis if it is formed by a Blandford-Rees (1974) twin-exhaust mechanism. Now as the two galaxies pass each other there will be an impulsive tidal force acting on each galaxy. If the stars respond to this impulsive force by "violent relaxation," then the minor axis of the stellar distribution with respect to absolute space can be altered. The gas cloud will then move to reestablish equilibrium, and in that process move the jet with it. This will cause the appearance of an inversion-symmetric jet. Note that this process does not explicitly depend on the angular momentum of the gas cloud.

If the halo can thus be (directly or indirectly) torqued during a close passage, it should effectively couple hydrodynamically to the jet since the crossing time of the galaxies (r/V_o) is of the same order as the inferred jet flow time to the lobes, assuming the slow jet speeds ($V_j \lesssim 1000$ km/s) which are inferred in several radio galaxies (e.g., Blandford and Icke 1978; Perley *et al.* 1979; Miley 1980; van Gronigen *et al.* 1980). We have only outlined two possible gravitational interactions. Obviously, tidal lags, ram pressure effects, and shocks may also cause observable tracers of the effects of the encounter.

If impulsive torques are responsible for this type of inversion-symmetric radio jets, we would expect two morphological subtypes: the Z and X shapes. The type that occurs depends on the dimensionless ratio of the two key time scales—the galaxy crossing time and the jet outflow time to the radio lobes. The Z shape results when the duration of the impulsive torque is long compared to the jet travel time, thus giving the jet a chance to continuously change direction during the tidal passage. The X shape results when the crossing time is very fast compared to the jet travel time, essentially instantaneously creating a new jet direction. There should be a noticeable difference in intensities and spectral indexes between the two legs of the X jet, as the old direction gradually fades out owing to synchrotron losses and the new direction is fed by the jets.

c) Circular Orbits and Wiggling Jets

Presumably, many of the bound pairs are in fairly circular orbits. Again, the simplest case is to assume a self-consistent potential. If this is so, one would expect an equilibrium of stars and gas to have been set up over several orbital periods. This "Roche lobe-like" configuration (balancing gravitational and centrifugal forces in a stationary pattern) might be stable against decay by dynamical friction for a time comparable to that inferred from observations ($\sim 10^9$ yr; Rood and Leir 1979). Because of the similarity of shape between the isophotes of systems such as NGC 750/1 and NGC 4782/3 (van Breugel 1981, private communication) and the Roche equipotential, it is tempting to propose a connection between db7 systems and these hypothetical contact binary galaxies. Until more data on velocity differences and isophotal shapes are available, we cannot definitely make such a connection. (Note that NGC 4782/3 is a high T-class system, but its ΔV of 640 km/s

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implies the dynamics are more likely dominated by nonluminous matter than by a self-consistent stellar potential.) Finally, we remark that if a Roche lobe geometry occurs, it is conceivable that new gas could be transferred to the radio member of the pair, thus providing the effect seen by Stocke (1978), i.e., that radio activity increases with decreasing separation in binary galaxies.

In the case of self-gravitating DG's with circular orbits, continuous tidal deformation will form an elongated star distribution and therefore gravitational potential along the line of centers of the galaxies. Therefore, if the jet direction is determined by the gaseous halo, either by the Blandford-Rees (1974) twin-exhaust method or the Sparke-Shu (1980) method, the jet direction must be along the minor axis and at right angles to the line of centers of the galaxies in the DG. Further, precession of the jet is very unlikely.

The radio source may well exhibit periodic mirror-symmetric wiggles in its jet induced by the orbital motion (see, e.g., Blandford and Icke 1978 for the case of an $e \simeq 1$ binary elliptical, 3C 31). If the ΔV is large enough, e.g., 3C 465 has $\Delta V \simeq 1100$ km/s, then the motion of the radio galaxy may produce a wide-angle tail, even though the center-of-mass motion of the DG through the cluster is near zero (this is the case of 3C 465; see Burns 1981). The relevant dimensionless parameter is $\Delta V / V_{\rm jet}$. This is small in the first case, producing a nearly straight jet with small-amplitude wiggles, and is large in the second case, causing a swept-back wide-angle tail. This information (wavelength and amplitude of wiggles) could be coupled with the (independent) optical data on spectra and isophotes, to solve for the dynamics of the system and perhaps settle the issue of the nature of the potential.

Our mechanism differs conceptually from other jet-bending scenarios previously discussed. In discussions of binary galaxy encounters (3C 31, Blandford and Icke 1978; 3C 449; Perley, Willis, and Scott 1979; IC 708, Vallée, Bridle, and Wilson 1981), the jet direction at the center of the galaxy has been assumed to stay fixed, while the direction of the galaxy changed. In our picture, both the central jet direction *and* the direction of the galaxy change simultaneously by the binary gravitational interaction. It remains to be seen whether one can fit such a model quantitatively to particular db's.

The future tasks are therefore at least twofold. First, we must determine whether these complicated gravitational, hydrodynamical, stellar-dynamical processes can occur for realistic values of elliptical galaxies. This requires detailed calculations, which we do not perform here. Second, we need to determine from the observational data how one can decide the questions (1)–(3) raised in this section. To illustrate the nature of this challenge, we present new observations on two dumbbell systems.

V. NEW OBSERVATIONS OF DB'S

We have made optical observations of two db's, NGC 326 and NGC 750/751. Although they are both elliptical galaxy systems, they differ in many observational details. Therefore we use them as prototypes for our morphological classifications outlined in Fig. 2 and for our dynamical arguments in Sec. III. We discuss their optical morphology, radio morphology, and redshifts. Finally, we have compiled a list of ~ 100 radio DG's on which more detailed observations are needed.

a) Optical Morphology

Following our decision tree, Fig. 2, we first describe the optical isophotes and their deviations from pure ellipticity. As a prototype of the undistorted db1 type we use NGC 326. We observed NGC 326 (4C 26.03) at KPNO in fall 1980 using the video camera on the 2.1-m telescope. Figure 3 shows the isophotes for NGC 326 derived from a 13-min exposure with a broadband V filter. There is clearly little distortion from sphericity in the two galaxies of this system (see also the lower-resolution isophotes in Battistini *et al.* 1980). The projected separation of the galactic centers is $6'' = 8$ kpc ($H_0 = 100\,\mathrm{km^{-1}\,s^{-1}\,Mpc^{-1}}$). We class the optical morphology of NGC 326 as db1[ED1, E1] with the ED1 galaxy (the northern one in Fig. 3) the radio galaxy. As Stocke *et al.* (1978) have noted, it often seems to be the

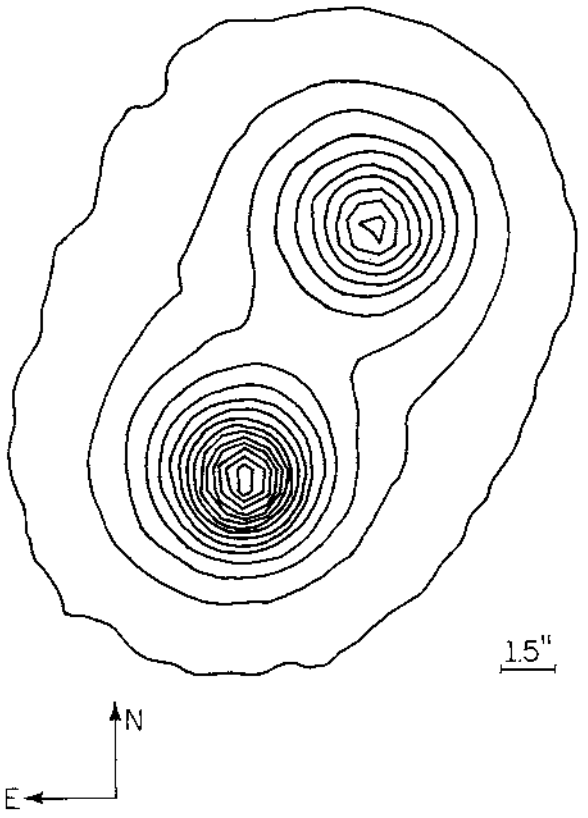


FIG. 3. Isophotal map of NGC 326 derived from 14-min V-passband exposure with same telescope/detector setup as Fig. 1, again in instrumental units. This map was produced with the kind assistance of R. Lynds at KPNO.

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D-type galaxy, in an E-D pair, which is the radio source.

On the other extreme of distortion, we use NGC 750/751 [Fig. 1(a)], which we class as db7[E4p, DE4p]. Previous photographs of this system are presented by Sandage (1961) and Arp (1966). Figure 1(b) presents isophotes for NGC 750/751 obtained from a *B*-bandpass video camera image taken with the KPNO 2.1-m telescope. The isophotal plots were produced using the Kitt Peak Interactive Picture Processing System and the GIPSY system at Groningen University. The magnitude difference is $\Delta B \simeq 0.3$ (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) with projected separation of 21″ (5 kpc). (This system certainly suggests large tidal distortions, in fact it may indicate that a stable configuration of stars and gas can be set up between two galaxies in close physical proximity.)

b) Radio Morphology

Moving down our "family tree" in Fig. 2, we next note that NGC 750/751 is radio quiet while NGC 326 is a classic inversion-symmetric radio jet. The radio morphology of NGC 326 has been discussed by Ekers *et al.* (1978). The map given there suggested a precessing beam model to those authors. We reproduce here (Fig. 4) a new 20-cm VLA map taken from Fomalont (1981) and Ekers (1981). This map suggests to us an X shape in which the "old beam" was from NE to SW and the "new beam," now building up double lobes, is from SE to NW. The projected length of the "old beam" is at least twice as long as the "new beam."

If one connects the "old" double lobes with the radio galaxy (solid lines in Fig. 4), one sees that a C symmetry exists suggesting the radio galaxy was moving through its cluster (Zw 0056.9 + 2636) in a projected direction (north = 0°) with p.a. ~ 150°. Connecting the "new" lobes to the radio galaxy (dotted lines in Fig. 4) also shows a C symmetry, but now the position angle of projected motion is ~ 210°. The swept-back angle is comparable before and after. This morphology strongly suggests that the radio galaxy has changed its velocity direction during its close passage with the other elliptical galaxy.

c) Redshifts

One of the key observational clues to the nature of db's is the redshift difference ΔV between the two galaxies. Once again our prototypes are quite different. Velocity measurements by Humason, Mayall, and Sandage (1956) show no measurable differential motion between the two galaxies NGC 750/751. By contrast, NGC 326 has a $\Delta V \simeq 750$ km/s (Sargent 1973). These ΔV's are to be compared to the typical velocity dispersion $\lesssim 300$ km/s of stars in elliptical galaxies and the velocity dispersion of $\simeq 1000$ km/s of galaxies in clusters.

d) Theoretical Interpretation

The low ΔV of NGC 750/751 taken together with its large tidal distortion and location far from any rich cluster suggests that it is a contact binary galaxy moving in its own self-consistent gravitational potential. It would be very helpful to find another such db, but with extended radio structure, to check our prediction of periodic wiggles in a jet emerging at right angles to the line of centers of the galaxies.

The large ΔV of NGC 326, the lack of tidal distortion, and its inversion-symmetric radio structure would seem to be a prototype for our model of tidal torquing during an impulsive close encounter. The lack of tidal distortion implies the galaxies are separating now with an actual separation nearly along the line of sight several times the projected separation. Because the galaxies are of equal size, it seems likely that their gravitational interaction could have both altered the space velocity of the radio galaxy and torqued its jet to a new direction. Since the new jet has been formed after the impulsive encounter in our picture, the velocity of the jet flow cannot be much greater than the ΔV of the galaxies (~ 1000 km/s) or it would have bored out to a much greater distance. We believe NGC 326 presents strong evidence for a class of Z shaped radio sources whose inferred precession has nothing to do with the "central engine."

e) Other DG's

There are at least two other radio galaxies with X morphologies which are DG's: 3C 315 (Högbom 1979) and 4C 48.29 (van Breugel 1980a; Bailey and Pooley 1968). We know of three examples of Z-shaped radio jets associated with DG's: 3C 310 (Burns and Owen 1979; van Breugel 1980a,b), 4C 39.04 (Fomalont and Bridle 1978), and 0238 + 085 (Fomalont *et al.* 1980a; Palimaka *et al.* 1980). Neither ΔV nor isophotes are available to check our hypothesis. In addition, we have a list of ~ 100 extended radio sources known or suspected to be DG's (Appendix B).* Clearly a methodical observational program of redshifts, optical photometry, and high-resolution radio maps of these objects is called for.

VI. CONCLUSIONS

Substantial evidence is accumulating that hot gaseous halos with scales of 10–100 kpc exist in many elliptical and radio galaxies. These are likely the confining mechanism of the jets *inside* the galaxy. The DG's are a unique probe of that gas, since the two galaxies may be close enough to dynamically affect each other on these scales.

The nature of the influence of the dynamics of the dumbbell system on the radio jets depends crucially on

*After this work was completed we received the note by Shaver *et al.* (1981) which refers to a complete sample of approximately 100 southern radio galaxies, about 10% of which show Z distortion in close (separation < 100 kpc) pairs of elliptical galaxies. We have not attempted to include their sample in ours, although there is some overlap. They find that as the separation between nearest-neighbor galaxies decreases, the degree of Z bending increases, in agreement with our model.

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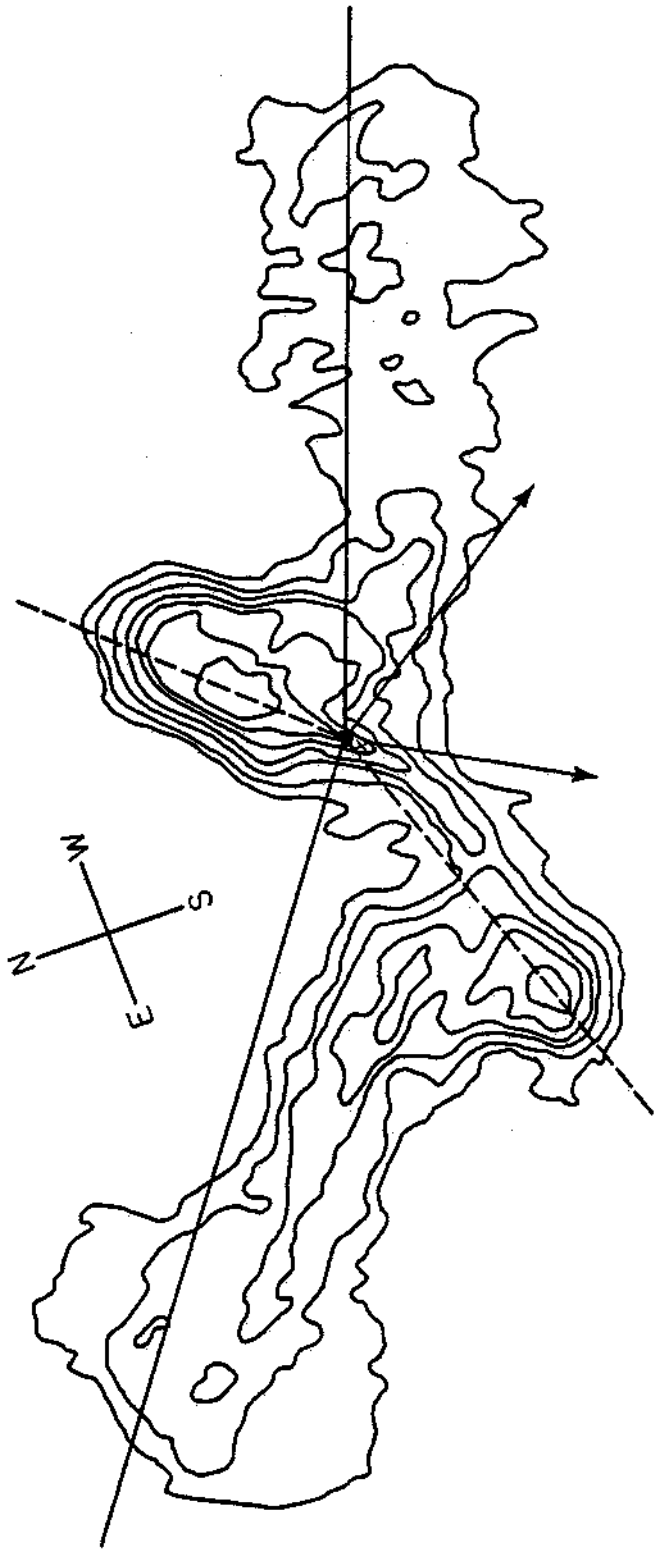


FIG. 4. This 20-cm VLA map of NGC 326 is adapted from Fomalont (1981) and Ekers (1981). We have superimposed lines connecting the radio galaxy with the "old lobes" (solid lines) and with the "new lobes" (dotted lines).

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TABLE I. Catalog.

NAMES		ZwCL AbCl		OPTICAL INFORMATION				RADIO INFORMATION			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
01 0008+32	B2	0008.9 +3207 A7	16.5	.1073 ?	?	3	1	1.15	2	WAT?	1
02 0051+166	4C16.2	(0048.5 +1540)	16.6	? ?	7	3	2	?	?	?	?
03 0055+285	4C26.03 NGC 326	0056.9 +2636	14.9	.0483 750	6	1	1,3,4	4.9	1	CX	1,5,6
04 0104+321	3C31 NGC 383/2	0107.5 +3212	12.1	.0163 280	35	2	1,7,25	9.9	1	C	1,16,26
05 0110+152	4CT15.03.1	0110.5 +1515 A160	13.6	.0445 ?	?	3	1,8	3.9	3	?	1
06 0116+319	4C31.04	0115.9 +3146?	15.7	.055 1140	24	3	1	3.5	3	?	1
07 0123-016	3C40 NGC 545/7	0123.6 -0133 A194	13.5	.0177 156	30	2	1,7,9	13.6	2	?	1,10
08 0158+293	4C29.05	0150.9 +3050?	15.7	.1482 ?	4	3	1	3.0	3	?	1
09 0220+427	3C66	A347	14.2	.0215 ?	25	1	1,25	23.0	2	C	1
10 0238+085	4C08.11 NGC 1044	0240.6 +0740	14.8	.0214 ?	20	3	1,8	2.7	2	Z	1,11
11 0255+058	3C75	0254.7 +0555 A400	14.7	.0241 360	16	1	1,2,7	14.3	2	?	1
12 0258+356	4C35.06A	A407	13.5	.0466 ?	mult. 10	2	1,17	2.0	2	?	1,17
13 0336-355	NGC 1399	FORNAX	10.9	.0045 900	15	3	1	5.6	2	?	1
14 0427-539		-----	13.2	.0402 240	12	2	1,31	10.4	2	?	1
15 0502-103		A536?	15.5	.0410 ?	?	3	1	4.0	3	?	1
16 0618-371		-----	16.6	.0326 ?	?	3	1	4.8	3	?	1
17 0703+426		0703.0 +4224	15.6	.075 ?	12	3	12	?	2	?	12
18 0821+157		A658	15.2	.126	?	3	35	0.78	3	?	35
19 0838+325	4C32.26	0837.6 +3238 A694/5	15.7	.0680 ?	15	3	1,8	1.6	2	?	1,12
20 0915-118	3C218 Hydra A	?	14.8	.0650 350	3	3	1,30	109.6	3	?	1
21 0933-047		A838	15	.055	?	3	35	0.42	3	?	35
22 1003+186		1005.3 +1840	14.2	.031 300	20	1	7	?	3	?	7

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TABLE I. (continued)

NAMES		ZwCL AbCl	OPTICAL INFORMATION					RADIO INFORMATION			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
23 1017+487	4C48.29	(1022.1 +4813) A1003	16	.052 ?	25	3	1,12,13	2.9	1	X	1,12,16
24 1040+317	B2	1037 +3134	15.6	.0360 ?	7	2	1	1.7	2	?	1
25 1045+31	B2	A1097	16.2	.09 ?		3	32				14
26 1053-28		-----	?	.06 ?	15	3	30	?	3	?	30
27 1108+272	NGC 3563	(1105.3 +2835) A1185	14.6	.0331 900	20	3	1,7	0.2	3	?	1,7
28 1113+295	4C29.41	1115.2 +3013 A1213	13.9	.0481 390	22	3	1	5.0	2	?	1
29 1142+198	3C264 NGC 3862	1142.1 +2126 A1367	14.0	.0208 ?	80	3	1	17.0	2	?	1,15
30 1159+583	4C58.23	A1446	15.3	.13 ?	6	3	14,32	?	2	C	14,36
31 1200+519	4CT51.29.1	A1452	16.5	.0631 ?	20		1				1
32 1204+225	4C22.33	1204.7 +2246	14.0	.0655 ?	18	3	1,12	?	1	WT	1,12
33 1209+746	4CT74.17.1	1209.9 +7440? A1500	14.1	.063 1000	8	1	16	?	1	wg	16
34 1227+119		A1552	14.1	.10 ?	?	3	32	?	3	?	29
35 1231+674	4C67.21	A1559	14.8	.12 ?	?	2	32,36	?	2	C	17,36
36 1252-122	3C278 NGC 4782/3	-----	13.5	.0145 640	40	1	1,37	14.6	3	?	1
37 1257+282	5C4.85	A1656 Coma	10.7	.0237 123	25	2	1	0.5	2	?	1
38 1317+334	NGC 5098	1317.9 +3350 A1714??	15.0	.0379 ?	45	3	1	0.24	3	?	1
39 1318+343		1317.3 3605	14.8	.0232 ?	?	3	38	0.22	3	?	38
40 1320+584		A1731	15.9	.15 ?	12	3	32	?	2	WAT	33
41 1339+266	4C26.41	1341.6 +2614 A1775	15.3	.0757 1800	20	1	1	1.3	2	?	1,10,17
42 1346+268	4C26.42	A1795	15.5	.0630 ?	?	3	1	3.15	3	?	1

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TABLE I. (continued)

NAMES		ZwCL AbCl		OPTICAL INFORMATION				RADIO INFORMATION			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
43 1352+24		A1819	15.7	.16 ?	?	3	32	?	3	?	14
44 1353+186	NGC 3227 Ma463	1354.0 +1834	14.8	.05 ?	5	1	27,28	?	3	?	27
45 1450+281		1449.9 +2813? A1984	16.5	.127 ?	10	3	1	0.4	2	?	1
46 1502+262	3C310	(1500.6 +2559)	15.3	.0543 670	20	3	1	23.4	1	Z	1,12, 16,24
47 1511+263	3C315	None	16.5	.1086 ?	7	3	1	16.5	2	X	1,18
48 1514+025	3C317	A2052	13.3	.0351	7	2	1,34	23.2	3	?	1,29
49 1525+291		1524.8 +2850 A2079	15.4	.0653 ?	?	3	1	0.4	2	?	1,10
50 1550+202	3C326	1550.1 +2019?	15	.0895 ?			39				39
51 1559+157		1600.4 +1925 A2147	15	? ?	?	3	1,29,35	4.66	2	?	1,29,35
52 1602+178	4C17.66 NGC 6047/5	A2151 Hercules	13.0	.0367 800	11	2	1,40	2.1	2	?	1
53 1626+396	3C338 NGC 6166	1625.5 +4006 A2199	13.1	.0303 1520	12.5	3	1	18.1	2	W	1,10,19
54 1630+056		A2204	14	.133	?	3	1,35	0.37	3	?	35
55 1736+329		None	16?	.0741 ?	?	3	1	0.6	3	?	1
56 1741+390	4C39.50	1744.5 +3846?	15	.0423 ?	?	3	20	?	3	?	20
57 1809+499	NGC 6582	1810.2 +4949?	14.8				42	0.06			42
58 1826+747		A2306	15.8	.15 ?	25	3	14	0.1	2	WAT	14,33
59 1842+455	3C388	1916+ 4855	15.3	.0908 ?			1	13.5			1
60 2104-257			13.5	.038 ?				?		?	
61 2121+248	3C433	None	16	.1016 ?	?	1	1	?	2	?	1
62 2130-536		-----	14	.0763 ?	?	3	1	3.7	3	?	1
63 2149-158		A2382	16	.007	?	3	32,35	1.4	3	?	35
64 2212+135	3C442 NGC 7236/7	2212.0 +1326	13.7	.0262 30	32	1	1,2,7	11.5	2	?	1
65 2229+391	3C449	2231.2 +3732	12.5	.0181 80	40		1	6.5			1

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TABLE I. (continued)

NAMES (1)		(2)	ZwCL AbCl (3)	(4)	OPTICAL INFORMATION (5)	(6)	(7)	(8)	(9)	RADIO INFORMATION (10)	(11)	(12)
66	2335+267	3C465 NGC 7720	2335.5 +2449 A2634	13.9	.0293 1060	12	1	1,7	20.2	1	Cwg	1,16
67	2357+004		None	16	.0839 ?	8	3	1	2.0	1	?	1,23

In addition to the above listed db's, there are 36 more known with either magnitudes less than 17 or z greater than .14. Since these may be too distant to obtain detailed optical morphology, we will only list their designations.

0100+256 (4C25.03)
0106+729 (3C33.1)
0136+396 (4C39.04)
0158+293 (4C29.05)
0203+05
0211+860 (3C61.1)
0258+435
0259+01 (4C01.06)
0344-291
0659+253 (3C172)
0719+670
0729+561
0757+640
0809+328 (4C32.24)
0837+613 (4C61.18)
0917+458 (3C219)
0924+606
1042+35
1104+365 (4C36.18)
1139-347
1151+295 (4C29.44)
1201-04 (4C-04.40)
1225+636
1231+674 (4C67.21)
1233+168
1247+503
1301+382 (4C38.35)
1303+366
1419+180
1420+198 (3C300)
1529+357 (4C35.36)
1602-634
1602+324 (4C32.5)
1726+538 (4C53.40)
2332+270 (4C27.53A)
2338-001

Reference key to Table I

1. Burbidge and Crowne (1979).
2. Zwicky (1961–1968).
3. Battistini *et al.* (1980).
4. This paper.
5. Ekers *et al.* (1978).
6. Ekers (1981).
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8. Palimaka and Bridle (1980).
9. Simkin (1976).
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11. Fomalont *et al.* (1980a).
12. Burns and Owen (1979).
13. Porcas *et al.* (1980).
14. Harris *et al.* (1980).
15. McHardy (1979).
16. van Breugel (1980a).
17. Simon (1979).
18. Högbom (1979).
19. Gavazzi and Perola (1980).
20. Rudnick and Adams (1979).
21. Westerlund and Smith (1966).
22. Schilizzi and McAdam (1975).
23. Fomalont and Bridle (1978).
24. van Breugel (1980a).
25. Butcher *et al.* (1980).
26. Fomalont *et al.* (1980b).
27. Casini and Heidmann (1978).
28. Adams (1977).
29. Owen (1974).
30. Ekers (1981, private communication).
31. Carter *et al.* (1981).
32. Leir and van den Bergh (1977).
33. Rudnick and Owen (1977).
34. Hoessel (1980).
35. Mills and Hoskins (1977).
36. Owen and Rudnick (1976).
37. van Breugel (1981, private communication).
38. Fanti *et al.* (1973).
39. Willis and Strom (1978).
40. Tarenghi *et al.* (1979).
41. Morgan and Lesh (1965).
42. Harris *et al.* (1977).

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the nature of the underlying gravitational potential. The primary source of the potential may be either the visible matter or the dark matter binding the cluster; the galaxies may be bound or unbound in this potential. If unbound (or in highly eccentric orbits), the galaxies could tidally torque each other's gaseous halo, causing an inversion-symmetric radio jet. For circular orbits we expect no inversion symmetry, but rather periodic wiggles (mirror-symmetric) or wide-angle tails caused by the orbital motion. In either case it is likely that some new gas will be dumped into the nucleus of the radio galaxy, fueling stronger radio activity. This effect has been discussed observationally by Stocke (1978).

By using DG's as probes of gaseous halos in radio galaxies, in many cases we are led to conclude that the galactic atmosphere has a stronger influence on observed jet properties than the central engine. These properties include jet existence, collimation, and direction. Further tests could be made by comparing VLBI maps ($\sim$1-pc scale) with VLA maps ($\sim$10-kpc scale). Misalignment on these scales should be common in db radio sources.

By eliminating the DG or multiple nuclei cD's from known Z-shaped radio galaxies, we are left with a sample in which the central engine itself may be precessing. Further high-resolution optical and radio observations of these candidate nuclei are essential.

We wish to thank R. D. Blandford, R. D. Ekers, T. Heckmann, V. Icke, C. Kotanyi, J. Oort, M. J. Rees, L. Rudnick, M. D. Smith, and W. van Breugel for useful conversations. We particularly appreciate the use of unpublished observational data by R. D. Ekers and W. van Breugel. A.W. gratefully acknowledges the help of H. Butcher and the KPNO staff during our observations. Special thanks go to R. Lynds for aid in reduction of the NGC 326 data and to K. Yoss for use of an unpublished plate of NGC 6166. J.S.G. would like to express his appreciation to the Kapteyn Astronomical Institute, University of Groningen, for use of the excellent GIPSY facility, where part of this work was done. He especially thanks R. Ekers, C. Kotanyi and J. van Gorkom for assistance with the computer and for many enlightening discussions concerning radio sources, and H. van Woerden for making his visit possible. Partial support was provided by the Faculteit der Wiskunde en Natuurwetenschappen, Rijksuniversiteit Groningen. L.S. gratefully acknowledges the research support of NORDITA in Copenhagen and the Max-Planck-Insitut für Astrophysik in Munich, where part of this work was completed. In addition, his work was partially supported by the Alfred P. Sloan Foundation. The work also received support from the National Science Foundation under Grant Nos. AST 79-09977 and PHY-80-01496.

APPENDIX

We have searched the literature for all known or suspected cases of radio galaxies with ud or db optical morphology. This sample is highly biased by the selection criterion and should not be considered a complete magnitude-limited sample. We include this list to encourage future observations of optical photometry, redshifts, and high-resolution radio maps, so that Table I can be "filled in."

The columns contain the following information:

Column 1: coordinates designation listed in order of increasing right ascension.

Column 2: other names from 3C, 4C, or NGC catalogs.

Column 3: Zwicky and/or Abell cluster membership. A set of parentheses means that the galaxy is near the edge of the cluster. "None" means no cluster is listed in Zwicky. A dashed line means the cluster is too far south to be in the Zwicky or Abell lists.

Column 4: approximate optical magnitude of galaxy. Warning—these values are taken from the literature and sometimes vary by several magnitudes from article to article.

Column 5: redshift of the radio galaxy and velocity difference between the pair of galaxies (km/s).

Column 6: separation of galaxy centers in arcseconds. "Mult." means there are more than two galaxies in the system.

Column 7: quality of published optical image: 1 = isophote, 2 = better observation than Palomar Sky Survey (PSS), 3 = PSS image.

Column 8: references to optical data. Only references not in Burbidge and Crowne (Ref. 1) are given.

Column 9: radio flux at 408 MHz—from Burbidge and Crowne.

Column 10: quality of radio map: 1 = VLA high-resolution map, 2 = lower-resolution map, 3 = no radio map.

Column 11: radio jet morphology: C = mirror symmetry, Z = inversion symmetry, X = crossed jets, W = large-scale mirror-symmetry wiggles, wg = small-scale wiggles, WAT = wide-angle tail.

Column 12: radio references not listed in Burbidge and Crowne.

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