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THE EXTENDED RADIO STRUCTURE OF COMPACT EXTRAGALACTIC SOURCES

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ABSTRACT

High dynamic range maps made with the VLA at 1.5 and 4.9 GHz of 21 luminous, core-dominated radio sources have clearly established the basic asymmetric disposition of the associated arcsecond-extended radio emission. This is in contrast with the generally symmetric brightness distributions of the less luminous, larger angular size sources. The asymmetry in this radio emission, many kiloparsecs from the radio core, may be caused by a Doppler enhancement produced by a relativistic bulk flow, or the asymmetry may be real.

Subject headings: BL Lacertae objects — quasars — radio sources: extended — radio sources: general — radio sources: variable

I. INTRODUCTION

Extragalactic radio sources have conveniently been classified into two categories: compact sources < 1″ in size, and extended sources > 1″ in size. However, it appears that most radio sources contain both compact and extended emission when observations of sufficiently high resolution and dynamic range are available. For example, VLB (very long baseline) observations of classical extended sources show that ~ 50% contain milli-arcsec cores (Schilizzi 1976; Gopal-Krishna, Preuss, and Schilizzi 1980). Similarly, high dynamic range observations of compact sources (Davis, Stannard, and Conway 1977; Perley, Johnston, and Fomalont 1980) have shown that many of this class contain extended emission of a few arcseconds extent near the compact core. From these early results, it could be supposed that there really is only one class of extragalactic radio sources, and that the previous separation into compact and extended categories was based on the relative dominance of the extended emission by the core.

The amount of core dominance may be understood by recent relativistic models of compact sources (Scheuer and Readhead 1979; Blandford and Königl 1979). In these models, the bright radio emission from compact sources is the Doppler-enhanced emission from a relativistic jet moving close to the line of sight. For jet flows with a Lorentz factor of ~ 5, the enhancement is of the order of 10^3, so that the jet emission could easily mask the isotropically radiating, extended emission. Observational support for this model comes from recent VLB observations (e.g., Kellermann and Pauliny-Toth 1981), which clearly show the presence of moving, one-sided jets in a number of compact objects.

A natural extension of these recent observational results and theoretical models then is to suppose that all luminous extragalactic radio sources have a "classical" morphology: two roughly equal large scale lobes which radiate isotropically, a compact core located within the galaxy from which the required energy for the lobes is generated, and two oppositely directed jets (not necessarily relativistic) which efficiently transport the energy to the lobes. The question we ask is whether the extended structure associated with the compact core-dominated sources is consistent with a classical structure whose small angular extent and bright core emission is caused by the source axis oriented near the line of sight.

In an attempt to answer this question, we have observed 21 core-dominated sources using the VLA (very large array) at 4.9 GHz with a resolution of 0″.7, and at 1.5 GHz with a resolution of 2″. The data were taken in 1980 February and June when the VLA was in a configuration with baseline lengths between 0.1 and 20 km.

All the sources were known *a priori* to contain arcsecond structure near a bright radio core, and many had previously been mapped at the VLA with lower resolution and sensitivity (Perley and Johnston 1979; Perley, Johnston, and Fomalont 1980; Ulvestad *et al.* 1981). No attempt was made to observe a complete

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sample of sources—rather, the intent was to map, with the highest dynamic range possible, sources known to exhibit arcsecond structure, so the sources selected were those exhibiting the most short-spacing excess flux on the basis of small amounts of prior data.

Here we present the overall results on 21 sources. Maps of these and other similar sources will be given elsewhere.

II. RESULTS

All sources contain an unresolved, dominant core at both frequencies. The additional emission is contained in several angular scales. Based on the relative prominence of the radio lobes, these sources can be classified into three groups:

1. *Completely one-sided.*—This corresponds to the D2 class of Miley (1971). Seven sources have only one detectable lobe (defined as a bright knot). In most of these cases, the flux ratio between the detected and undetected lobes is large: exceeding 10:1 for all sources, 100:1 for 3C 454.3, and 250:1 for 3C 273. An example of this type of morphology in the source 3C 454.3 is shown in Figure 1.

2. *Two-sided sources.*—Thirteen sources display two lobes besides the compact core. The ratio of lobe brightnesses is high, usually exceeding 5:1, but not as high as the limits set for the one-sided sources. The source structure is often misaligned, and the two lobes often display very different morphologies. An example of this class, 0224+671, is shown in Figure 2.

3. *Complex.*—Many sources contain a wide range of structure, including jets (or elongated structures), lobes, and extensive diffuse emission. However, only one source, 0716+714, does not have at least one radio lobe detected with these observations. Figure 3 shows a two-sided source which contains more complex emission.

Radio maps were made of all 21 sources at both frequencies. Relevant parameters are given in Table 1, which is arranged as follows: Columns (1) and (2) give the IAU and common name of the source; columns (3) and (4) show the identification type and the redshift; columns (5), (6), and (7) give the total angular extent, the total linear extent, and the radio luminosity (ergs s^{-1} Hz^{-1}) emitted using $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$; columns (8), (9), (10), and (11) list the flux density at 5 GHz measured for the source (total), the radio core, the lobes and jet, and for any additional extended emission with angular size $> 5''$. Columns (12), (13), (14), and (15) give similar information at 1.5 GHz. The estimate of the extended flux density was made from the analysis of the visibility amplitude and the clean components. Column (16) displays the morphology of these core-dominated sources (1S = one-sided; 2S = two-sided; CH = core halo), and column (17) lists the flux density ratio between the lobes.

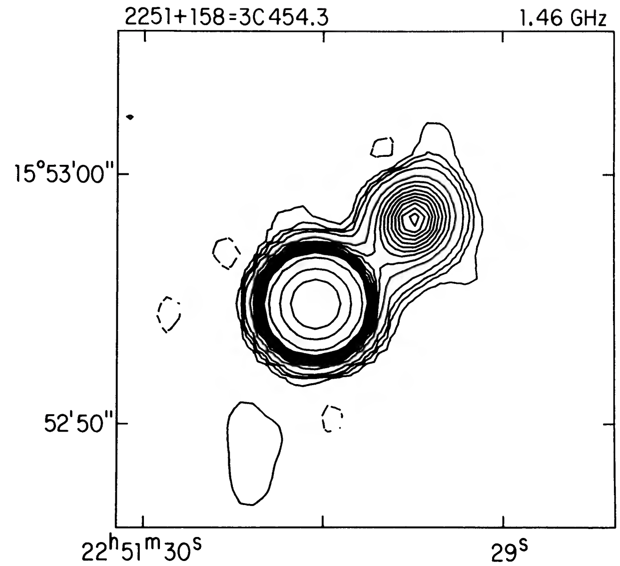

FIG. 1.—An example of a one-sided source, 3C 454.3 at 1.46 GHz with 2″ resolution. The contour levels are −0.1, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.25, 1.5, 2.0, 3.0, 4.0, 5.0, 7.5, 10, 25, and 50% of the peak of 9.65 Jy.

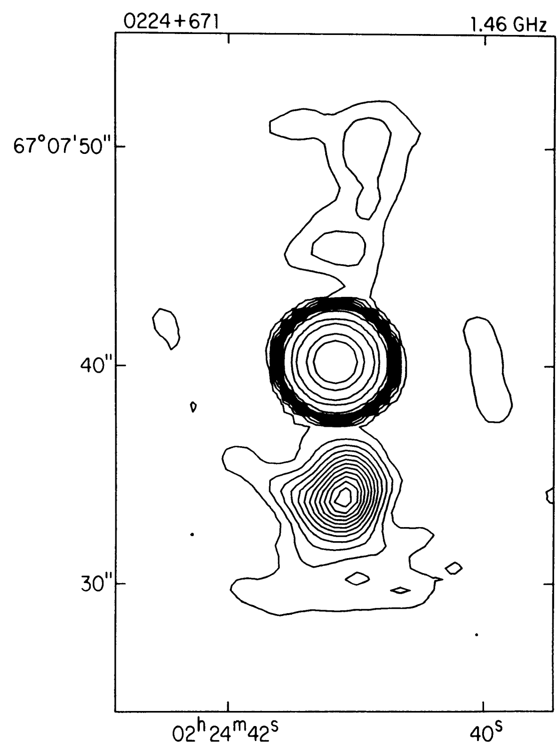

FIG. 2.—An example of a two-sided source, 0224+671 at 1.46 GHz with 2″ resolution. The contour levels are −0.1, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.5, 2, 3, 4, 10, 25, and 50% of the peak of 1.39 Jy.

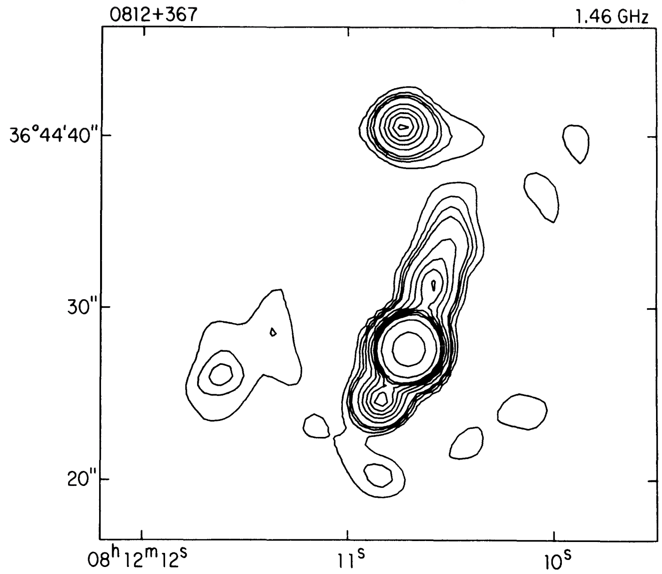

FIG. 3.—An example of a source with complex emission, 0812+367 at 1.46 GHz with 2″ resolution. The contour levels are −0.3, 0.3, 0.6, 0.9, 1.2, 1.5, 2.2, 3.0, 4.0, 5.0, 6.0, 9.0, 15, 22, 30, and 50% of the peak of 0.68 Jy.

TABLE 1
PARAMETERS FOR 21 CORE-DOMINATED RADIO SOURCES

Source		ID		Ang. size	Lin. size	Lumin.	5 GHz (Jy)				1.5 GHz (Jy)				Morphology		Notes
IAU	Name	Type	Z	Asec	kpc	10^{33}	Total	Core	Lobes	Ext	Total	Core	Lobes	Ext	Class	Ratio	
0056+665				11			0.43	0.23	0.15	0.05	0.92	0.35	0.4	0.15	2S	2	*
0224+671		BL?		20			1.18	1.13	0.04	0.03	1.55	1.38	0.07	0.10	2S	5	
0716+714		BL		17			0.85	0.70		0.15	0.90	0.48		0.42	CH		*
0812+367		Q	1.025	13.5	57.7	5.4	0.94	0.82	0.08	0.05	1.05	0.71	0.21	0.13	2S	1	*
0859+470	4C47.29	Q	1.462	1.45	10.4	25.	1.63	1.53	0.10	0.02	2.25	2.00	0.25	0.02	1S	10	
0900+428	4C42.28	GAL		18			0.83	0.65	0.13	0.05	1.30	0.90	0.20	0.20	2S	6	
0923+392	4C39.25	Q	0.699	1.9	7.6	19.	7.4	7.2	0.1	0.1	2.70	2.0	0.7		2S	1.5	*
0954+556	4C55.17	Q	0.909	3.0	12.7	13.	2.08	1.85	0.15	0.08	3.05	2.66	0.24	0.15	1S	15	
1150+497	4C49.22	Q	0.334	8.2	24.0	0.6	0.97	0.56	0.15	0.25	1.70	0.60	0.30	0.80	2S	3	*
1226+023	3C273	Q	0.158	21.4	38.0	7.1	34.7	29.4	5.3	0.5	49.0	33.1	15.9	0.5	1S	250	*
1253−055	3C279	Q	0.536	12.3	45.2	20.	10.6	9.40	1.20	0.1	10.1	7.50	2.60	0.2	2S	1	*
1415+463	4C46.29	Q	1.522	11.8	50.6	7.1	0.74	0.66	0.08	0.02	0.80	0.48	0.32	0.05	2S	10	*
1636+473	4C47.44			17.0			0.65	0.52	0.13	0.02	0.88	0.44	0.40	0.05	1S	100	*
1641+399	3C345	Q	0.594	2.8	10.6	21.	8.40	7.80	0.30	0.10	7.85	6.88	0.50	0.30	2S	10	*
1642+690	4C69.21	Q		10			1.85	1.75	0.08	0.02	1.50	1.17	0.23	0.10	2S	8	
1656+571	4C57.28	Q	1.293	1.6	6.9	5.1	0.58	0.47	0.06	0.05	0.85	0.47	0.13	0.35	2S	5	
1751+441		Q	0.871	20	84.2	3.9	1.01	0.95	0.06	0.02	0.68	0.52	0.10	0.06	2S	20	
1800+440		Q	0.660	3.0	11.8	1.8	0.68	0.55	0.10	0.03	0.83	0.53	0.15	0.15	2S	7	
1807+698	3C371	GAL	0.051	25.0	17.0	.04	1.95	1.52	0.30	0.13	2.35	1.35	0.50	0.50	1S	10	*
1823+568	4C56.27	Q		4.0			1.75	1.55	0.15	0.05	1.40	0.95	0.30	0.10	1S	40	
2251+158	3C454.3	Q	0.859	5.33	22.2	49.	8.90	8.59	0.30	0.10	10.40	9.70	0.70	0.20	1S	100	

NOTES.—0056+665: Flux decomposition is uncertain. 0716+714: No discernible radio lobe. 0812+367: Diffuse structure east of source. 0923+392: Flux decomposition at 1.5 GHz uncertain. 1150+497: Extensive halo with angular size ~ 20″. 1226+023: Flux density ratio limit of lobes is > 500:1. 1253−055: Z-shape morphology. 1415+463: Brighter lobe is double. 1636+473: Radio lobe is double. 1641+399: Surrounded by a 15″ faint halo. 1807+698: Complex halo about 2′ in size.

Finally, an asterisk in column (18) indicates that a note concerning the source is given below Table 1.

Because of the manner in which these objects were selected for study, no attempt was made to assess the significance of the relative number of objects in each category. However, two correlations may be significant: (1) the percentage of emission from the core is somewhat higher for the most luminous sources, and (2) the completely one-sided sources are among the most luminous of the group.

III. DISCUSSION

It is clear that the underlying emission visible with our resolution and dynamic range is very asymmetric and is not typical of normal double sources. The detected radio lobes are well separated from the core, so the asymmetries cannot be ascribed to the lack of dynamic range in the maps or in the blending of the radio components because of projection effects. Statistics of classical doubles (Fomalont 1969; McKay 1971; Neff and Rudnick 1980) show that the majority of these objects have a flux ratio of $< 2{:}1$ between the lobes. Less than 10% show ratios $> 5{:}1$. In contrast, most of our sources have lobe-brightness ratios greater than 5:1. Thus the extended structure of compact sources is more asymmetric than that of classical doubles.

It has been argued by Browne *et al.* (1981) that there is still significant larger scale emission which is missed by high-resolution arrays such as the MERLIN or the VLA. It is this emission which corresponds to the symmetric lobes, while the asymmetric structure, which is observed, corresponds to a Doppler-enhanced core and a jet with a relativistic flow near the line of sight. Such missing large-scale emission can often be inferred from the discrepancy between the flux density of a source derived from a single antenna with that from an array, although confusion from nearby sources for single antenna observations can be a problem. However, examples of such discrepancies suggested by Browne *et al.* (1981) of 10% of the total flux density for the sources 1636+473, 1642+690, and 2251+158 are not substantiated with the VLA observations where the limits are less than 2%. In any case, the morphology of the extended emission must be determined before its nature can be inferred.

However, it is possible that the large-scale symmetric emission is still below the sensitivity of our observations. For example, consider a model for 3C 273 derived from recent VLB observations. The apparent superluminal motion implies a minimum of $\gamma = 10$ (where $\gamma = (1 - \beta^2)^{-1/2}$ with $\beta =$ bulk flow velocity in the source) occurring at an angle $\theta = 6°$ with the line of sight. The flux enhancement for these values is $[\gamma(1 - \beta\cos\theta)]^{-3-\alpha}$, where α is the spectral index defined as $S \sim \nu^{-\alpha}$, and the enhancement is 7×10^4 for this model of 3C 273. If the unenhanced ratio of the core to the extended flux density is 10^{-3} using Cyg A as a standard, then the enhanced core in 3C 273 should emit 70 times more emission than the extended component.

The presence of asymmetric structures does strongly argue that the simple model comprising a weak core, symmetric lobes, and a *non*relativistic jet (or jets) supplying the lobes is not tenable. This is simply because this model cannot give the observed asymmetric structures.

There are two possible explanations for the source asymmetry:

1. The sources are intrinsically symmetric, but *relativistic motion* of the kiloparsec-sized jet and lobes has enhanced one side, producing the observed asymmetry (Perley, Johnston, and Fomalont 1980; Browne *et al.* 1981).
2. The extended structure is intrinsically asymmetric.

The relativistic interpretation receives support from comparison of our data with VLB data. Of our 21 sources, 8 have good quality VLB maps which show parsec-sized jets or core elongations in a position angle within $\sim 20°$ of that defined by the arcsecond structure. This alignment indicates a possible connection between the milli-arcsec and arcsecond jets. This inference is made stronger in 3C 345 and 3C 454.3 where a jet is connected between the milli-arcsec and the arcsecond structure. Since four of the sources (3C 345, 3C 454.3, 3C 273, and 3C 279) have confirmed or suspected superluminal motion near the core, relativistic motion in the jet and lobe many kiloparsecs from the core may also be occurring.

The approximate motion velocities associated with the superluminal source 3C 273 follow. If β_{ob} is the apparent velocity (in units of c) in the plane of the sky, then the minimum bulk Lorentz velocity β of the flow which could produce the observed superluminal motion β_{ob} is

$$\beta^2 = \frac{\beta_{ob}^{\ 2}}{1 + \beta_{ob}^{\ 2}}\,.$$

This minimum condition occurs when the flow is $\theta = \cos^{-1}(\beta)$ from the line of sight. The measured β_{ob} for 3C 273 is ~ 10 (Pearson *et al.* 1981; Cohen *et al.* 1979). These values of β_{ob} and θ lead to a value of $\beta\cos\theta$ (velocity in the line of sight) of 0.99. Smaller values can be obtained with larger θ to about $\beta\cos\theta \sim 0.97$.

The asymmetry for 3C 273 radio jets and lobes as measured by the ratio of flux density on each side of the core is $> 500{:}1$. Again, with mildly relativistic bulk flow, these asymmetries can be explained by values of $\beta\cos\theta$ of only 0.67, a value considerably less than that needed to explain the superluminal motion of the milli-arcsec jet.

These asymmetric sources could arise from classical, symmetric double sources (like Cyg A) if the following were true: (1) The axis of the source and the direction of the bulk flow were within about 15° of the line of sight. (2) Within about 10–100 pc of the core, flow velocities were about 99% the speed of light and thus cause a flux enhancement of about 10^5. (3) Somewhat lower velocities, about 50% c, would produce the asymmetries of about 20:1 in the kiloparsec jets. (4) The bright knots of radiation at the end of the jets are probably the radio lobes. To reproduce the typical asymmetry of the lobes requires mildly relativistic motion of about 0.25. Such a high bulk velocity of a radio lobe seems unlikely. Alternatively, these bright knots may be intermediate regions in the jet where the velocity might be high, but where there is significant radiation.

On the other hand, the asymmetries of the kiloparsec structure may be intrinsic and not caused or significantly enhanced by relativistic flow of material in the line of sight. Perhaps we are observing a source whose central engine switches from side to side on a time scale comparable with the age of the source (Willis 1978).

This asymmetry often occurs for jets detected in low-power radio galaxies such as NGC 315, NGC 6251, 3C 219, and 3C 31 (e.g., Bridle 1981). The origin of these asymmetries is unknown but is unlikely to be based on relativistic bulk flow, since the curvature and wiggles in these jets are convincingly explained by subrelativistic flow velocities.

At present we cannot distinguish between these two models for the asymmetric kiloparsec structure associated with the most luminous sources using radio morphological arguments. The asymmetry may be intrinsic to the source formation or may be produced by a bulk relativistic flow near the direction of the line of sight. It appears that the most useful work can be done at the milli-arcsec scale with VLB techniques. Examples are:

1. Measuring the proper motion of the arcsecond structure to directly measure relativistic motion. There is, for example, a very small scale knot in the "A" component of 3C 273 (Perley, Johnston, and Fomalont, in preparation) whose motion with respect to the core could be measured with VLB techniques.

2. Following the motion of the milli-arcsec-scale superluminal knots of 3C 273 and 3C 345 to larger angular sizes in an attempt to measure their deceleration. Significant deceleration would suggest nonrelativistic motion in the lobes.

3. Finding many more superluminal sources, so correlations between superluminal velocity and arcsecond structure asymmetry can be attempted.

These tests are very difficult, but they are needed to further elucidate the nature of core-dominated sources.

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