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VLBI Observations of a Mixed Selection of Extra-galactic Objects

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Summary. *VLBI* observations at 6 cm reported of several weak radio cores of normal and Seyfert galaxies, of radio sources which have jets or a head tail morphology as well as some stronger cores of flat spectrum galaxies from the NRAO-Bonn "S 4" survey. Nearly all sources were detected at an angular resolution of approximately 15 milli arc s. Some of the sources are resolved at this level.

Key words: galaxies – *VLBI*

1. Introduction

In November 1978 we made short *VLBI* observations at a wavelength of 6 cm of a mixed selection of objects using the 1.6 km Westerbork Synthesis Radio Telescope (WSRT) as an adding interferometer (with an equivalent collecting area of ~ 93 m and a $6'' \times 10'$ fan beam response) and the Onsala 25 m telescope. In March 1979, the program was repeated with the Effelsberg 100 m telescope as an additional element. The objects observed were chosen from samples being studied for various reasons in other programmes of the authors and consist of normal and Seyfert galaxies, radio sources which have jets or a head tail morphology and some galaxies with strong flat spectrum cores from the NRAO-Bonn "S 4" survey. The fringe spacings of the *VLBI* network range from 10 to 40 milli arc s at 6 cm wavelength. Several of the nearby objects have structure on this angular scale.

2. The Observations

A description of the observational and reduction procedures for the March 1979 observations is given in Schilizzi et al. (1979). Similar procedures were applied to November 1978 observations. Additional corrections to the fringe amplitudes were made to allow for decreases in the antenna performances at low elevations and to allow for the effect of shadowing of antennas at short spacings at Westerbork. The coherent integration time was 5 min.

In Table 1 the correlated flux densities of the various objects are given for the three baselines. In the first two columns the names of the objects are given; column 3 gives the morphological type of the galaxies. E=elliptical; L=lenticular; S=spiral; I=irregular; P=peculiar; Q=quasar; G=galaxy with unspecified morphology. For the NGC galaxies this description is taken from de Vaucouleurs et al. (1976) and for the other objects we have followed the current descriptions in the literature. In columns 4–6 the measured correlated flux densities (in mJy) are given for the three different baselines. The appropriate UV-coordinates (in $10^6\,\lambda$) can be found in the columns 7–9. WE = Westerbork-Effelsberg; EO = Effelsberg-Onsala, WO = Westerbork-Onsala. If a source was observed but not detected, this is indicated by: <. If a source was not observed on a certain baseline or when no reliable upperlimit could be set there is a blank in the appropriate column. *d* means a detection but due to inaccurate positions and the small WSRT beam no accurate Flux density could be given.

For the most part the errors in these flux densities were determined from the $\sim 6\%$ uncertainty in the calibration factors and the r.m.s. noise (Schilizzi et al., 1979). In those cases where a source was not detected, an upper limit of 15, 40, 60 mJy/beam can in general be given for the Westerbork-Effelsberg (WE), the Effelsberg-Onsala (EO), and Westerbork-Onsala (WO) baselines respectively.

3. Discussion

Notes on the detected sources are given in Table 2. The comments on the small angular scale structure refer to our *VLBI* measurements which are compared with other *VLBI* data as well as with the flux densities measured with single dishes or conventional radio interferometers. Some of the sources have been mapped with conventional interferometers with sufficient detail and sensitivity to make comments on the extended structure; these are given in the last column of Table 2.

In general, our *VLBI* measurements show good agreement, with other data when available from the literature. However, we find higher flux densities than have been found with conventional interferometers for the head-tail radio galaxies with weak cores: NGC 1265; 3C 129, IC 711, 1615+35, and 4CT 51.29.1.

In principle compact components (typically $\lesssim 0''.015$) may cause confusion of the core flux density if 1. these components lie within the common primary beams of the telescopes, and 2. the differential fringe rates of these components with respect to that of the core, are small enough (typically $\lesssim 3$ mHz for a 5^{m} integration) not to be distinguished from the fringe rate maximum of the core. Maps of these sources made with the VLA and the WSRT (Owen et al., 1978, 1979; Vallée and Wilson, 1976) have shown the existence of "knots" near the core which are unresolved at $\sim 1''$ (VLA) or $\sim 6''$ (WSRT) resolution. Since the flux densities of most of these knots are 3–4 mJy, several such knots with angular sizes $\lesssim 0''.015$ would be needed in order to explain the above mentioned confusion.

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Table 1

Normal Galaxies			Correlated Flux density in mJy			(U,V) coordinates in ($10^6\lambda$, $10^6\lambda$)		
			WE	EO	WO	WE	EO	WO
0239-08	N 1052	E	673 ± 41			2.35, 2.34	-	-
			538 ± 32			-1.39, 2.25	-	-
					589 ± 38	-	-	8.73, 4.49
0428+01	N 1587	E	<			3.01, 2.76	-	-
			<	<	<	-1.26, 2.78	1.96, 7.61	2.93, 4.83
					<	-	-	8.64, 4.73
					<	-	-	-1.02, 4.84
0931+10	N 2911	L	d	164 ± 13	d	2.65, 3.10	11.49, 7.73	8.84, 4.67
						-	-	0.25, 6.24
						-	-	7.92, 5.37
0956-27	N 3078	E			<	-	-	7.95, 2.49
					<	-	-	3.92, 0.66
0959+56	N 3079	S		<		2.56, 3.52	+1.40, 6.27	8.83, 3.04
				<		-	-6.53,12.21	-
					<	-	-	7.61, 640
1122+39	N 3665	L			<	-	-	-3.25, 8.86
			30 ± 7			-2.64,-3.57	-	-
					<	-	-	7.53, 0.78
					<	-	-	0.47, 9.24
1212+55	N 4194	I	<	<	<	-3.27, 2.61	-7.22,11.80	-4.19, 9.11
				<		-	9.67, 9.66	-
					<	-	-	8.78, 1.90
					<	-	-	-1.85, 9.80
1218+30	N 4278	E	241 ± 15	173 ± 13	180 ± 16	-3.50, 2.44	-9.86, 9.59	-6.54, 7.07
				240 ± 18		-	9.42, 9.90	-
						-	-	0.83, 3.89
						-	-	-2.79, 5.88
1227+08	N 4472	E	<	<	<	-3.39, 2.84	-8.22, 8.58	-5.12, 5.74
				<		-	8.41, 8.55	-
					<	-	-	8.80, 4.82
					<	-	-	-2.79, 5.88
1233+13	N 4552	E	85 ± 9	<	<	-3.43, 2.82	-8.68, 9.02	-5.55, 6.15
			91 ± 12	<	<	0.41, 3.44	7.10, 9.34	6.40, 5.98
					<	-	-	8.56, 5.12
1317-12	N 5077	E	d			0.16, 1.92	-	-
					<	-	-	8.72, 4.32
					<	-	-	8.38, 4.02
1754+18	N 6500	S		<		1.53, 3.59	9.74, 9.13	8.10, 5.62
			d	144 ± 12		-2.44, 3.39	-2.74,10.68	-0.58, 7.28
						-	-	0.38, 7.29
						-	-	8.46, 3.69
Head Tail Radio Galaxies								
0315+41	N 1265	L	36 ± 6			2.88, 3.37	-	-
			38 ± 6	<	<	0.64, 4.34	7.69,11.43	6.90, 7.23
					<	-	-	8.71, 2.51
					<	-	-	-0.43, 9.42
0445+45	3C 129	G	35 ± 4	<	<	2.63, 3.57	11.47, 6.81	8.84, 3.47
			45 ± 5	<	<	-0.73, 4.36	3.74,13.11	4.27, 8.83
					<	-	-	7.49, 6.68
					<	-	-	0.37, 9.60
1131+49	IC 708	E	66 ± 5			-2.57,-3.59	-	-
				<		-	-3.20,13.39	-
					<	-	-	7.68,-0.21
					<	-	-	3.26, 9.32
1132+49	IC 711	E	57 ± 8, 39 ± 8	<	<	2.36, 3.75	11.17, 7.45	8.74, 4.12
				<		-	-4.02,13.18	-
					<	-	-	8.07, 0.39
					<	-	-	1.66, 9.67
1615+35	N 6109	E	41 ± 6	<	<	2.35, 3.73	11.16, 8.09	8.77, 4.52
			24 ± 4	<	<	-2.44, 3.68	-2.73,12.64	-0.50, 8.96
					<	-	-	8.73, 2.24
					<	-	-	2.36, 9.10
2334+27	N 7720	L	271 ± 17	294 ± 19	303 ± 22	1.26, 3.92	9.18, 9.94	7.78, 6.13
					327 ± 25	-	-	8.42, 5.45
					263 ± 32	-	-	-2.48, 8.37

Table 1 (continued)

Radio galaxies, quasars, Seyferts			Correlated Flux density in mJy			(U,V) coordinates in ($10^6\lambda$, $10^6\lambda$)		
			WE	EO	WO	WE	EO	WO
0055+30	N 315	L		647 ± 40		-	-2.62,12.19	-
					585 ± 41	-	-	8.83, 4.32
					568 ± 40	-	-	-2.48, 8.37
0240−00	N 1068	S	<			2.10, 2.74	-	-
				<		-	5.47, 7.47	-
					<	-	-	0.82, 4.74
					<	-	-	7.54, 4.74
0844+32	4C 31.32	E	47 ± 5	<	<	3.11, 3.17	11.65, 5.99	8.59, 2.92
			44 ± 5	<	<	1.93, 3.87	10.51, 9.04	8.48, 5.35
					<	-	-	7.41, 1.48
					<	-	-	3.01, 8.42
1200+52	4CT 51.29.1	G	47 ± 5			-3.16,-2.88	-	-
					<	-	-	8.52, 1.08
					<	-	-	0.21, 9.88
1208+40	N 4151	P	<	<	<	-3.19, 3.03	-6.70,11.85	-3.75, 8.77
				<		-	10.09, 9.50	-
					<	-	-	8.66, 2.51
					<	-	-	-1.07, 9.25
1502+26	3C 310	E	<	<	<	-2.75, 3.41	-4.32,11.51	-1.79, 8.08
			<	<	<	2.21, 3.66	10.96, 8.49	8.67, 5.03
					<	-	-	8.79, 3.85
					<	-	-	-0.31, 8.15
1722+34	4C 34.47	Q	204 ± 13	148 ± 10	386 ± 26	-2.11, 3.84	-1.28,12.72	0.50, 8.90
					422 ± 30	-	-	1.59, 8.82
					471 ± 33	-	-	7.49, 1.27
2229+39	3C 449	E	<	<	<	-3.38, 2.69	-8.16,11.07	-5.11, 8.23
			44 ± 5	<	<	0.59, 4.30	7.57,11.41	6.77, 7.27
					<	-	-	8.08, 5.94
					<	-	-	-6.05, 7.75
Strong "Flat spectrum" galaxies								
0258+35		G	25 ± 4	<	<	1.03, 4.17	8.66,10.63	7.44, 6.63
			<	<	<	3.22, 3.03	11.56, 5.23	8.44, 2.37
					<	-	-	8.17, 1.93
					<	-	-	0.67, 8.95
0309+41		G	382 ± 23	356 ± 25	378 ± 26	3.18, 3.02	11.60, 4.81	8.54, 2.05
					432 ± 30	-	-	8.32, 1.59
0402+37		G	540 ± 33	546 ± 34	576 ± 35	2.60, 3.60	11.44, 7.31	8.84, 3.92
					572 ± 40	-	-	8.64, 4.73
					821 ± 57	-	-	0.63, 9.17
0733+59		G	360 ± 22	417 ± 27	394 ± 29	3.45, 1.89	10.89, 0.17	7.60,-1.52
					386 ± 39	-	-	7.99,-0.88
					363 ± 36	-	-	1.94, 9.84
0831+55		G	4940 ±296	2522 ±152	2419 ±147	2.88, 3.19	11.64, 4.88	8.81, 2.02
					3708 ±260	-	-	3.32, 9.44
					3818 ±267	-	-	7.26,-1.49
1146+59		G	665 ± 40			-3.19,-2.64	-	-
					403 ± 28	-	-	8.48, 0.26
					553 ± 39	-	-	0.60,10.01
1652+39		G	920 ± 55	624 ± 38	643 ± 40	2.55, 3.64	11.39, 7.36	8.83, 3.94
				278 ± 18		-	-1.74,13.14	-
					794 ± 56	-	-	8.37, 2.24
1743+55		G	275 ± 17	255 ± 17	238 ± 19	-2.09, 3.86	-1.22, 3.81	0.58, 9.96
					256 ± 26	-	-	1.77, 9.83
					258 ± 41	-	-	7.51,-1.18
1807+69	3C 371	G	1779 ±107	1733 ±104	1561 ± 94	-2.05, 3.60	-1.06,13.49	0.69, 9.91
					1433 ±100	-	-	1.79, 9.76
					1244 ± 87	-	-	7.52,-2.73

We note that it is not impossible that several knots of very small angular size exist in the streamers or jets of head-tail galaxies. High resolution observations of the radio jet in M 87 have shown that several of its knots are unresolved at $\sim 0.''5$ level (Wilkinson, 1974). If the knots in the head-tail galaxies are of similar linear size to those in M 87, then angular sizes of $\lesssim 0.''08$ (NGC 1265), $\lesssim 0.''10$ (3 C 129), and $\lesssim 0.''07$ (IC 711 and 1615+35) can be expected.

In the cases of 3 C 129, 1615+35, and probably also IC 711, the two criteria mentioned above are satisfied, and confusion of the correlated core flux densities by several unresolved ($\lesssim 0.''015$) knots is indeed possible in our observations, but for NGC 1265,

Table 2

Normal Galaxies		Small scale structure	Large scale structure
0239-08	N 1052	Unresolved, in agreement with Cohen et al. (1971), ≤ 0.001" at 3.8 cm, and Shaffer and Marscher (1979), ∿ 0.0034" at 18 cm. The compact component has a flat radio spectrum (Fosbury et al., 1978) and is variable (Heeschen and Conklin, 1975; Ekers, priv. comm.).	Extended component of ∿11" at 21 cm (Hummel, 1980) and ∿21" at 11 cm (Heeschen, 1968 and 1970)
0931+10	N 2911	At 6 cm with low resolution (< 7") Ekers and Ekers (1973) observed 150 mJy. At 13 cm Crane (1979) measured a size of ∿0.008" (14 ± 2 mJy). The spectrum is flat (Ekers and Ekers, 1973; Ekers, priv. comm.).	
1122+39	N 3665	Weak source	Small double structure (∿ 30" at PA ≃ -45°) Kotanyi,(1979).
1218+30	N 4278	The core has a spectral index of ∿ 0.2 (Ekers and Ekers, 1973; Condon and Dressel, 1978; Hummel, 1980). At 18 cm Shaffer and Marscher (1979) measure an angular size of ∿ 0.0052" but with twice the flux of our measurements.	
1233+13	N 4552	Unresolved. The core is variable (Sramek, 1975(b); Ekers, priv. comm.) and has a spectral index of 0.1 (Sramek, 1975(a); Condon and Dressel, 1978; Hummel, 1980).	
1317-12	N 5077	Probably unresolved because interpolation of the 11 cm and 3.7 cm data given by Condon and Dressel (1978) (NRAO 300 ft. telescope) yields 96 mJy at 6 cm using their spectral index of 0.3, which is similar to the flux density that we have measured.	
1754+18	N 6500	Elongated or multiple structure. Interpolation of the 11 cm and 3.7 cm data given by Condon and Dressel (1978) yields 151 mJy at 6 cm using their spectral index of 0.2, which is similar to what we find on the EO baseline at PA ≃ -14°.	
Head-Tail Radio Galaxies			
0315+41	3C 83.1	Probably unresolved. Note that the flux densities that we find are higher than found by Owen et al. (1978) (∿20 mJy, ≤0.1") and by Ryle and Pooley (1975) (21 ± 3 mJy, ≲ 0.8"). See text.	Well known head-tail radio galaxy (∿9') (e.g. Miley et al., 1975; Owen et al., 1978).
0445+45	3C 129	Our VLBI data indicate that the core is unresolved since at low resolution (≲ 7") van Breugel (1980, IV) measures 34 ± 4 mJy at 6 cm. Maps made at ∿1" resolution (Owen et al., 1979) show however that ∿6 mJy of the above flux density must be attributed to a one sided jet and that the core has a flux density of ∿ 28 mJy. One of our VLBI observations is consistent with this, the other marginally. See text.	Well known head-tail radio galaxy (∿ 30') (e.g. Miley, 1973; Owen et al., 1979).
1131+49	IC 708	Vallée and Wilson (1976) measure ∿114 mJy at 6 cm (≲ 7") thus there must be some extended emission on an angular scale between 0.05" and 7".	Wide angled head-tail source (∿1.5'); together with IC 711, member of Abell cluster A 1314 (Vallée and Wilson, 1976)
1132+49	IC 711	The core (57 ± 8 mJy) has a somewhat higher density than found by Vallée and Wilson (1976) (44 ± 3 mJy, < 7") at 6 cm. See also text.	Very long (∿ 14') head-tail source (Vallée and Wilson, 1976; see also IC 708).
1615+35	N 6109	Ekers et al. (1978) measure ∿ 54 mJy (≤ 7") and Owen et al. (1979) ∿ 25 mJy (< 1"). One of our VLBI observations is consistent with the latter result. The other is somewhat too high.	Long head-tail source (∿ 11') (Ekers et al. 1978).
2335+27	3C 465 N 7720	Unresolved, in agreement with Walker et al. (1976) (300 mJy, ≲ 0.05" at 6 cm).	Wide angled head-tail source (∿ 8.5') (e.g. van Breugel, 1980 (II)).

Table 2 (continued)

Radio Galaxies Quasars, Seyferts		Small scale structure	Large scale structure
0055+30	N 315	Unresolved. VLBI flux agrees with Bridle et al. (1979) who measure 620 mJy (< 1") at 6 cm.	Giant radio source (∿ 30') with a very long jet (e.g. Bridle et al., 1979).
0844+32	4C31.32	Unresolved. At lower resolution van Breugel (1980, II) measures 55.0 ± 1.5 mJy (≤ 7") at 6 cm.	Radio source (∿ 6') with a one sided jet (van Breugel, 1980 (II)).
1200+52	4CT51.29.1	Harris et al. (1980) find 46 mJy at 6 cm (≤ 7"). Owen et al. (1979) report 22 mJy (≤ 1"). Our value is consistent with that of the former authors.	Complex head-tail or one sided jet radio galaxy (Miley and Harris, 1977; Owen et al., 1979).
1722+34	4C34.47	Resolved in a position angle comparable to that of the whole source. Conway et al. (1977) find 508 mJy (≤ 7") at 6 cm. The core is probably variable, (Van Breugel, priv. comm.).	Identified with a QSO, this radio source has the largest angular size (∿ 4') in its class (Conway et al., 1977).
2229+39	3C 449	May be unresolved (≤ 0.05") since Perley et al. (1979) report 37 ± 1 mJy (≤ 0.4") at 6 cm.	Twin jet radio source (Perley et al. 1979).

Strong "Flat Spectrum" Galaxies		Small scale structure	Large scale structure
0258+35		Weak source. Pauliny-Toth et al. (1978) measure 926 ± 20 mJy (≤ 2'.7) at 6 cm with the Effelsberg 100 m telescope. Aperture synthesis maps are required to map the missing flux.	
0309+41		Most of the flux density is probably from an unresolved component, although some weak emission may be in larger scale structure. Kapahi (1979) measures 456 ± 30 mJy (≤ 2") at 6 cm.	An extended, steep spectrum component has been found at 21 cm 87" from the core at PA = -28° (Kapahi, 1979).
0402+37		Most of the flux density is probably from an unresolved component. Since Kapahi (1979) measures 1114 ± 30 mJy (≤ 2") at 6 cm, some ∿ 500 mJy must be in another component within 2" of the core.	
0733+59		Unresolved. Kapahi (1979) measures 576 ± 30 mJy (≤ 2") so that weak emission must exist beyond the core, but within 2".	
0831+55		Resolved (∿ 0.02"). Kapahi (1979) measures 5785 ± 60 mJy (≤ 2") so that some emission must exist beyond the core but within 2".	
1146+59		Resolved (∿ 0.02"). Kapahi (1979) measures 615 ± 30 mJy (≤ 2"), so that some emission must exist beyond the core but within 2".	
1652+39		Resolved (∿ 0.02"). Pauliny-Toth et al. (1978) measure 1420 ± 30 mJy (≤ 2.7'), so that some emission must exist beyond the core but within 2.7'. VLBI observations at 6 cm (Weiler and Johnston, 1980) with a $10^8\lambda$ baseline show a correlated flux density of 390 mJy in a milliarcsecond structure.	
1743+55		Unresolved. Pauliny-Toth et al. (1978) measure 521 ± 8 mJy (≤ 2.7') so that some emission must exist beyond the core but within 2.7'.	
1807+69	3C 371	Resolved (∿ 0.02"). Cohen et al. (1971) measured 500 ± 60 mJy (≲ 0.001") at 3.8 cm, which is considerably less than our value at 6 cm, giving further evidence of resolution effects on these scales. Recent VLA observations at 6 cm (Perley and Johnston, 1979) show a secondary component of normal spectral index with 100 ± 20 mJy, 3.25" ± 0.2" away in PA = -120° ± 20°. There also may be structure on scales of ∿ 10" not shown in their map. The low resolution map at 21 cm by Högbom and Carlsson (1974) shows weak extended emission in approximately the same PA.	Pauliny-Toth et al. (1978) measure 2230 ± 80 mJy (≤ 2'.7), which taken together with our VLBI results confirms the existence of extended emission outside the core region of 0.02".

the two criteria are not satisfied and confusion does not seem likely. In the case of IC 711 there is also a second peak in the fringe rate spectrum with a flux density of 39 ± 8 mJy which lies in the same delay channel as the core component but at a differential fringe rate of ~100 mHz. There is no evidence of compact structure of this flux density within the common primary beams of the telescopes, apart from the core source (see map by Vallée and Wilson, 1976). The probability that a spurious of 5–6σ occurs in one of the 50–75 independent sample points per delay channel is $\sim 10^{-3}$ (Moran, 1976). Taking all sources together, we searched ~1800 such delay channels, and so a spurious peak of this signal-to-noise ratio is not unexpected in at least one source. If, however, we regard its occurrence in the same delay channel as the core source as significant, then the probability of its being spurious is reduced by a factor of 10.

To check our results, it seems worthwhile to reobserve these sources with the European *VLBI* network, using a better UV-coverage, as well as with conventional interferometers with $<1''$ resolution.

Of the head-tail sources, IC 708 seems to have structure on an angular scale between $0''.05$ and $7''$ (see Table 2). Comparing the structure of this source observed with $\sim 7''$ resolution [Vallée and Wilson (1976)] with that of similar head-tails which are mapped at $\sim 1''$ resolution (e.g. Owen et al., 1979) it is likely that the flux density of the core measured by Vallée and Wilson (~114 mJy) partially includes the emission of one or two jets within $\sim 7''$ from the nucleus.

Also resolved are the nearby ($z = 0.2055$) quasar 4 C 34.47 and most of the "strong flat spectrum galaxies". Several of these sources also have large scale radio structure. The galaxies appear to be related to BL Lac objects (Kapahi, 1979) and are potential candidates for monitoring for super-light expansions.

From our observations it is clear that one can successfully use *VLBI* networks to study the structure of a variety of (relatively nearby) objects at faint flux density levels. Since the nuclei of galaxies are generally believed to play a dominant role in the formation and further evolution of extra galactic radio sources, it is of crucial importance to study the structure of the radio cores in as much detail as possible. Comparison with the more extended radio and optical emission may eventually reveal more about the physical processes occurring in the galactic nuclei.

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