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The compact radio structure of the high redshift quasars 0642+449, 1402+044, 1614+051

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Abstract. In the first stage of an investigation of possible cosmological evolution effects in the compact radio structure of quasars, we have used a combined European and US VLBI network to image the milliarcsec scale morphology of three quasars with redshifts greater than 3. The sources 0642+449 ($z=3.406$) and 1402+044 ($z=3.208$) display weak distorted jets, while 1614+051 ($z=3.212$) is slightly resolved. The jets in 0642+449 and 1402+044 are the most distant known in the universe.

Key words: quasars – VLBI – jets

1. Introduction

One of the most pressing questions in cosmology concerns the space density of quasistellar objects, and their evolution with time. Despite more than twenty five years of observation in the optical and radio, and more recently at X-ray wavelengths the true nature of quasars is still obscure, the lifetimes of individual objects are unknown, and the extent of cosmological evolution in density or luminosity has not yet been established.

An important subset of the quasar population are the radio quasars, important because they are amongst the most luminous objects in the universe and are therefore relatively easy to study, and because their morphologies can be studied in great detail with interferometry even at very great distances. Information on the evolution of radio sources with cosmological epoch can be obtained by comparison of their properties in widely spaced redshift ranges.

Factors affecting the comparison of observed radio structures of quasars in different redshift ranges are fourfold: (i) *Cosmological properties of the universe.* Widely spaced redshift ranges correspond to widely separated cosmological epochs. For example, at $z\sim3{,}5$, the age of the universe is $\sim10\%$ of its present age [using $t=t_0(1+z)^{-3/2}$], while at $z\sim0.5$, it is 50% of its present age. The average matter density at the epoch corresponding to $z=3.5$ is about 30 times higher than for $z=0.5$ [$\rho=\rho_0(1+z)^3$]. In addition, for most world models, the angular size of a cosmological measuring rod is not a linear function of the distance to the object, and changes only slowly for the range of redshifts discussed. In the absence of intrinsic evolution in the objects, the angular size should be approximately the same for the redshift ranges $3.0\leq z\leq4.0$ and $0.5\leq z\leq1.0$. (ii) *Evolution of the objects themselves with cosmological epoch.* (iii) *The local environment of the radio source.* (iv) *The propagation medium between the object and observer through which the radio waves must propagate.* If matter exists along the propagation path, scattering of the radio waves may be important owing to electromagnetic effects as well as gravitational lensing.

One may therefore expect to observe evidence of general cosmological effects as well as specific evolution effects in the structures of radio sources at different redshifts. There are indications that the observed properties of radio quasars vary as a function of redshift. In one of the first attempts to use radio-loud quasars in cosmology, Miley (1971) found evidence for cosmological evolution of their radio dimensions. Barthel (1986), and Barthel & Miley (1988) have shown that the 0.1–1 arcsec scale structures of distant steep-spectrum (e.g. extended) quasars are more distorted than a luminosity-matched sample at lower redshift. However, this result is not confirmed by Kapahi (1990). Wehrle et al. (1989, 1990) report finding more distortion in the milliarcsec structures of quasars at moderate redshift than in low redshift objects. Swarup et al. (1986) noted a high fraction of associated optical absorption line systems ($z_{abs}\sim z_{em}$) in compact radio-loud quasars, suggestive of dense gaseous environments. Such environments were also postulated by Lonsdale & Barthel (1987). The linear sizes of both quasars and radio galaxies apparently decrease with redshift, with a dependence varying from $(1+z)^{-(1.1\pm0.5)}$ for $\Omega_0=0$ and $(1+z)^{-(1.45\pm0.4)}$ for $\Omega_0=1$ (Eales 1985) to $(1+z)^{-(3.0\pm0.5)}$ for $q_0=0.5$ (Kapahi 1989).

In addition, Cohen and collaborators (Cohen et al. 1988; Wehrle et al. 1990) are examining the cosmological evolution of the proper motions in radio-loud quasars, in an attempt to

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Send offprint requests to: R.T. Schilizzi constrain parameters describing the geometry of the universe. The general aim of the present work is complementary and seeks to study the epoch dependence of the milliarcsec scale morphology of radio quasars by comparing the structures of objects with redshifts greater than 3 with a control sample having redshifts less than 1.

We have selected a sample of eight quasars for 5 GHz observations with the combined European and US VLBI Networks, and a further seven objects for observation with the Southern Hemisphere VLBI Network. This paper presents results of VLBI observations of three objects of our sample: 0642+449, 1402+044, and 1614+051. The following section describes the sample; Sect. 3 gives details of the observations, calibration, and data reduction; and Sects. 4 and 5 provide a discussion on the results.

2. The sample

The 15 objects in the sample are all those satisfying the following criteria: (1) 5 GHz flux density greater than 100 mJy, and (2) redshift $z>3$ (see Table 1). It is very likely that the sample is representative rather than complete since not all radio sources at our limiting flux density have been optically identified. Moreover, the effects of flux boosting and/or anisotropic radiation in radio-loud quasars are far from understood (Orr & Browne 1982; Barthel 1989). The comparison sample at low redshift will be selected from the literature and will comprise the most luminous radio quasars with $z \leq 1$ observed at 10.7 and 22 GHz [in order to compare properties at the same emitted frequency: $\lambda_{\mathrm{emitted}} = \lambda_{\mathrm{observed}}/(1+z)$]. The radio luminosities of the sample objects are given in Table 1; they are comparable with the luminosities of the strongest quasars at lower redshift, e.g. 3C 279 which has $\log L_{5\,\mathrm{GHz}} = 27.80\ \mathrm{W\,Hz^{-1}}$.

VLBI maps have been published for two sources in our list: 0014+81 and 2000−330. The first is resolved at 6 cm on transatlantic baselines (Kühr et al. 1986) into a compact component with an extension to the south at a separation of ~0.8 milliarcsec. This structure is aligned with the (small) arcsec structure observed by the same authors with the VLA. The source 2000−330 was found to be unresolved by Preston et al. (1989) at 2.3 GHz using a beam of ~50 milliarcsec.

Radio spectra of the 3 sources described in this paper are shown in Fig. 1 and references for the flux densities are given in Table 2. The spectra can be described as humped, or having a plateau, at gigahertz frequencies as is typical of high redshift quasars (Peterson et al. 1982; O'Dea 1990).

3. Observations, calibration and data reduction

The three sources (0642+499, 1402+044, 1614+051) were observed in left circular polarization at 4.99 GHz in sessions in 1986 and 1987 (see Tables 3 and 4). The data were recorded using the Mark II NRAO VLBI system (Clark 1973) with 1.8 MHz bandwidth, and correlated on the Caltech-JPL correlator (1402+044), or the MPIfR correlator (0642+449 and 1614+051). Integration times of 60 s were used and the correlation coefficients converted to flux densities (Cohen et al. 1975) using system temperatures measured during the observations and predetermined gain curves for the individual telescopes. The calibration was adjusted by up to 15% using sources assumed to be unresolved on intra-continental baselines (0235+164, 1404+287) and on inter-continental baselines (1739+52, 0552+398). The final calibration is consistent from station to station at the 2% level.

Examination of the visibility amplitudes versus projected baseline for 0642+449 and 1402+044 (Figs. 2a, b) indicates that these two sources are dominated by strong point-like components. 1614+051, on the other hand, shows a gradual drop in amplitude as the projected baseline length increases, indicative of slightly resolved structure (Fig. 2c). As the first stage of reconstructing images of these sources, the visibility phases of all

Table 1. The sample of high redshift quasars

Source	Other names	RA(1950)[a]	DEC(1950)[a]	z[a]	$S_{5\,\mathrm{GHz}}$ (mJy)[a]	$\log L_{5\,\mathrm{GHz}}$ ($\mathrm{W\,Hz^{-1}}$)[b]
0014+813		00 14 04.1	+81 18 28	3.384	550	27.65
0335−122		03 35 33.3	−12 13 51	3.45	380	27.50
0420−388		04 20 29.9	−38 51 50	3.12	107	26.89
0537−286	OG-263	05 37 57.0	−28 41 28	3.119	990	27.86
0636+680		06 36 47.4	+68 01 28	3.174	540	27.60
0642+449	OH 471	06 42 53.0	+44 54 31	3.406	778	27.81
0938+119		09 38 31.8	+11 59 13	3.19	190	27.15
1351−018		13 51 32.0	−01 51 20	3.709	820	27.88
1402+044		14 02 30.0	+04 29 55	3.208[c]	710	27.73
1442+101	OQ 172	14 42 50.6	+10 11 12	3.531[c]	1150	28.00
1614+051		16 14 09.1	+05 06 54	3.212[c]	850	27.81
1935−692		19 35 11.8	−69 14 52	3.170	760	27.75
2000−330		20 00 12.9	−33 00 15	3.775[c]	1030	27.99
2048+312	CL4	20 48 47.4	+31 16 11	3.185	700	27.72
2126−158		21 26 26.7	−15 51 51	3.275	1240	27.98

[a] Source coordinates, redshifts and flux densities are taken from Véron-Cetty & Véron (1989).
[b] Radio luminosities have been calculated assuming $H_0 = 75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.5$, $\alpha = 0$ (von Hoerner 1974).
[c] Redshift updates taken from Barthel et al. (1990).

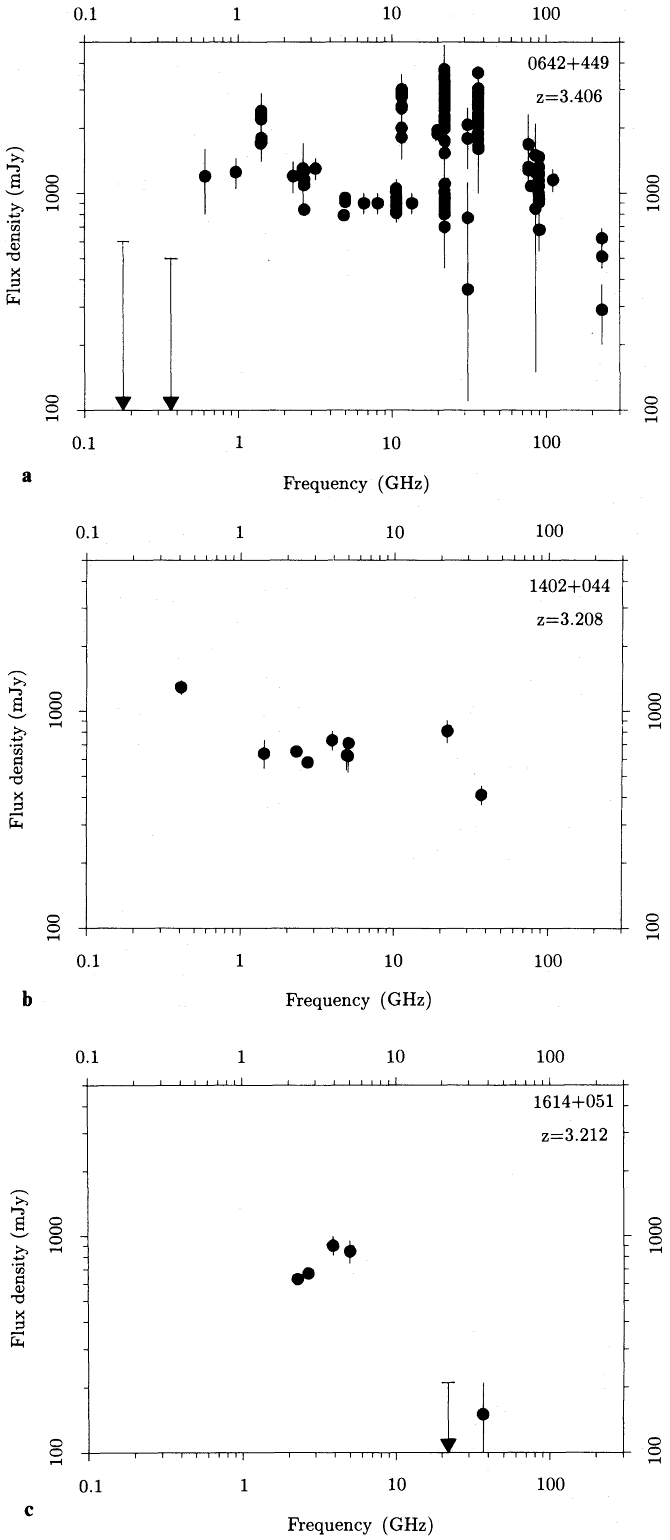


Fig. 1a–c. Radio spectra of **a** 0642+449, **b** 1402+044, and **c** 1614+051, compiled from the literature listed in Table 2. The vertical lines indicate the errors in flux density

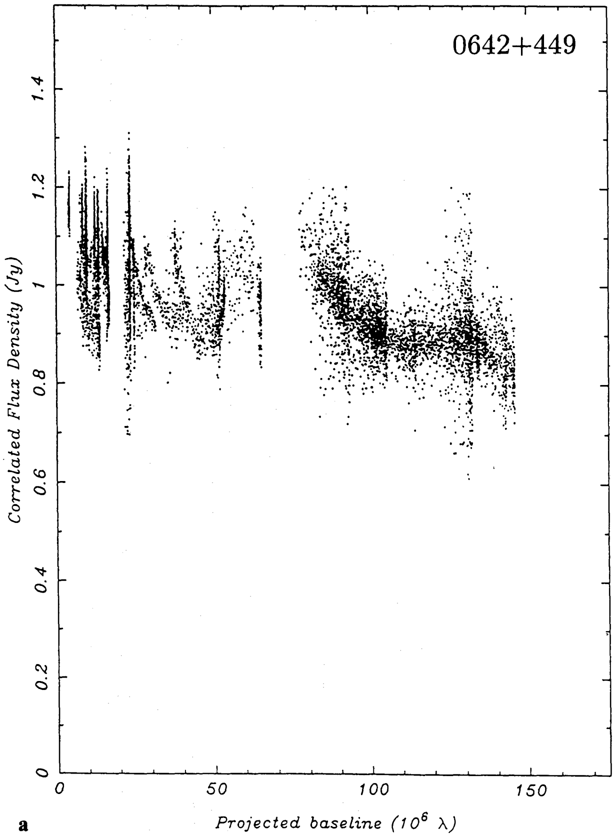
three sources were roughly aligned using point sources as input models; the flux densities of the point sources were estimated from Fig. 2 as 0.9, 0.6 and 0.6 Jy for 0642+449, 1402+044 and 1614 +051, respectively.

Table 2. References for spectral data

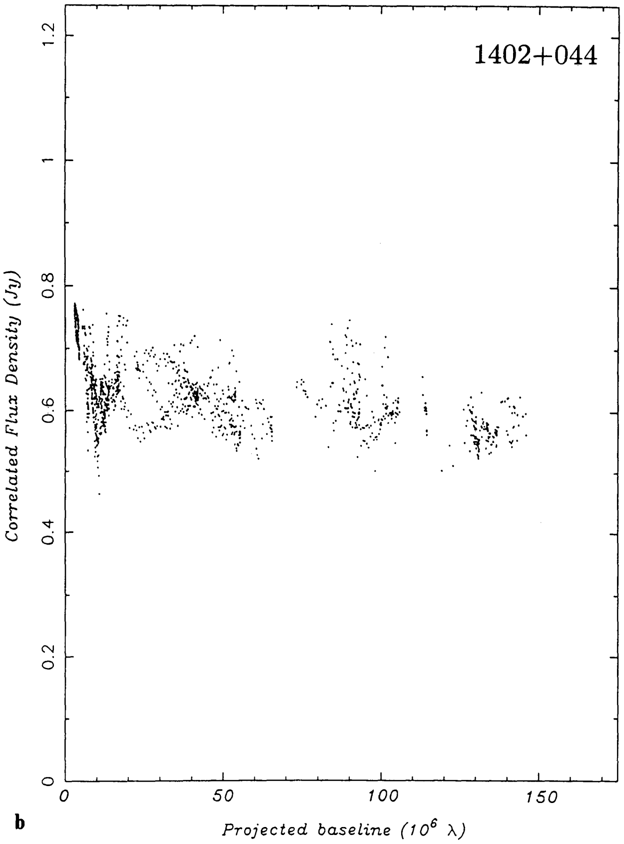
Frequency (GHz)	References		
	0642+449	1402+044	1614+051
0.0167	1		
0.025	1		
0.178	1		
0.365	1		
0.408		16	
0.612	1		
0.966	2		
1.40	1		
1.415	1	12	
2.29	6	6	6
2.65	1		
2.7	1, 2, 11	15	15
3.2	1		
3.9		5	5
4.90	2	12	
5.0	1, 7	15, 16	15, 16
6.6	1		
8.09	1		
10.695	1, 2		
11.6	14		
13.5	1		
20	10		
22.2	1, 14	3	3
31.4	1		
36.8	14	3	3
77	9		
80	4		
85.3	1		
90.0	2, 4, 8		
111.	10		
230.	4		
311.6		13	

References: 1. Gearhart et al. (1974); 2. Kühr et al. (1979); 3. Valtaoja (1990); 4. Steppe et al. (1988); 5. Larionov (1989); 6. Preston et al. (1985); 7. Miley & Hartsuijker (1978); 8. Owen & Puschell (1982); 9. Teräsranta et al. (1987); 10. Edelson (1987); 11. Kesteven et al. (1976); 12. Feigelson et al. (1984); 13. Robson et al. (1985); 14. Salonen et al. (1987); 15. Shimmins et al. (1975); 16. Parkes Catalogue (1990).

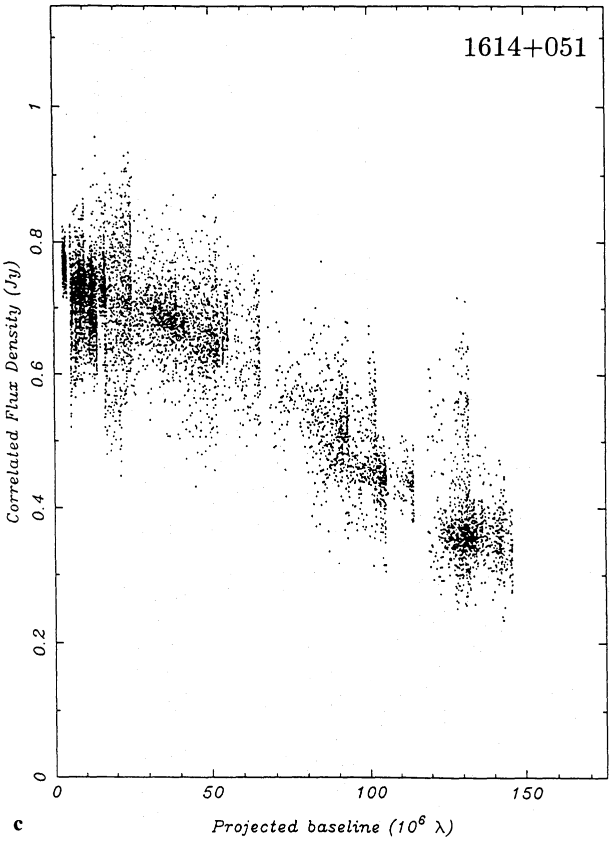
Standard image reconstruction practice involving phase and amplitude self-calibration was followed using the Caltech VLBI package to generate the images shown in Fig. 3. The CLEAN delta functions fit the data (not shown) within the noise. The reality of the extended features seen in the images of 0642+449 and 1402+044 has been tested by windowing them out and checking the fit to the data. In all cases the fit deteriorated significantly when one or more of the weak features was omitted. However, in view of the low surface brightness of the extended



a



b



c

Fig. 2a–c. Correlated visibility amplitude versus projected baseline for **a** 0642+449, **b** 1402+044, and **c** 1614+051

Table 3. Epochs of VLBI observations and used stations

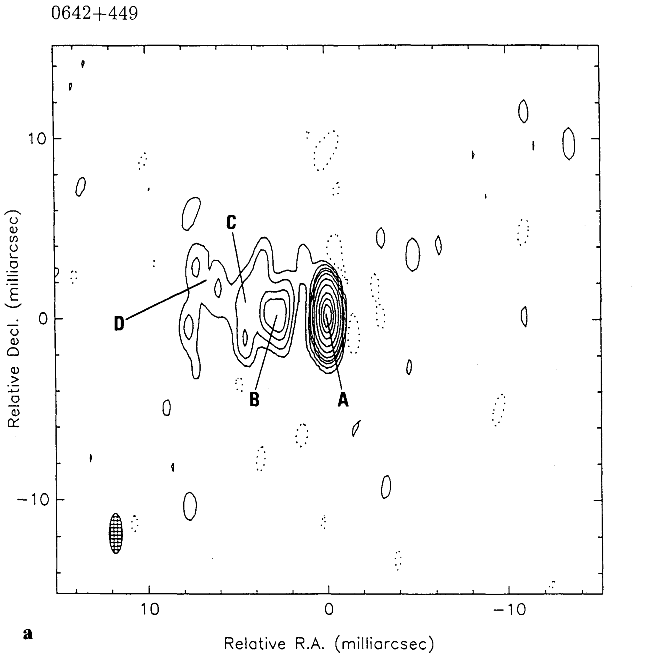
Source	Epoch	Stations[a]
0642+449	1987.734	B, F, G, K, L, O, S, W
1402+044	1986.89	B, G, K, L, O, S, W, Y
1614+051	1987.732	B, F, G, K, L, O, S, W, Y

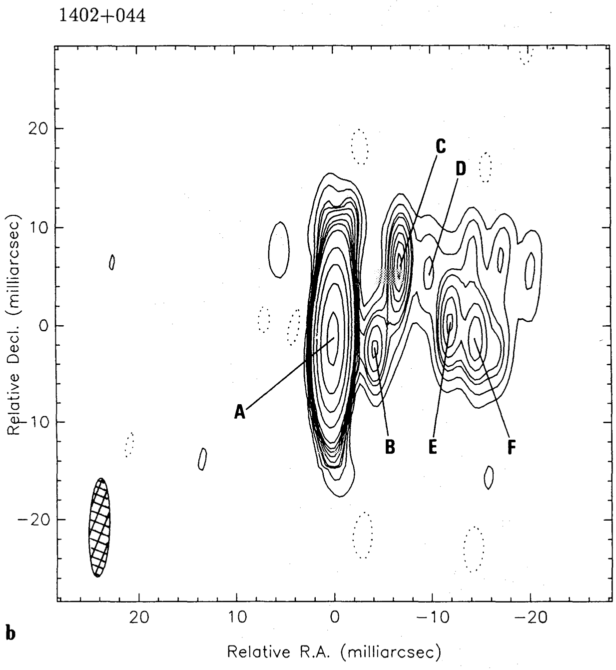
[a] Station codes are listed in the Table 4.

Table 4. Stations and their characteristics

Code	Station	Diameter (m)	System temperature (K)	Sensitivity (K/Jy)
B	Effelsberg	100	60	1.450
F	Fort Davis	26	70	0.092
G	Green Bank	43	45	0.276
K	Haystack	36	70	0.161
L	Medicina	32	55	0.180
O	OVRO	40	55	0.270
S	Onsala	26	70	0.060
W	WSRT[a]	93	100	1.050
Y	VLA[a]	130	55	2.500

[a] The WSRT and VLA were used in phased array mode; equivalent diameters are given.





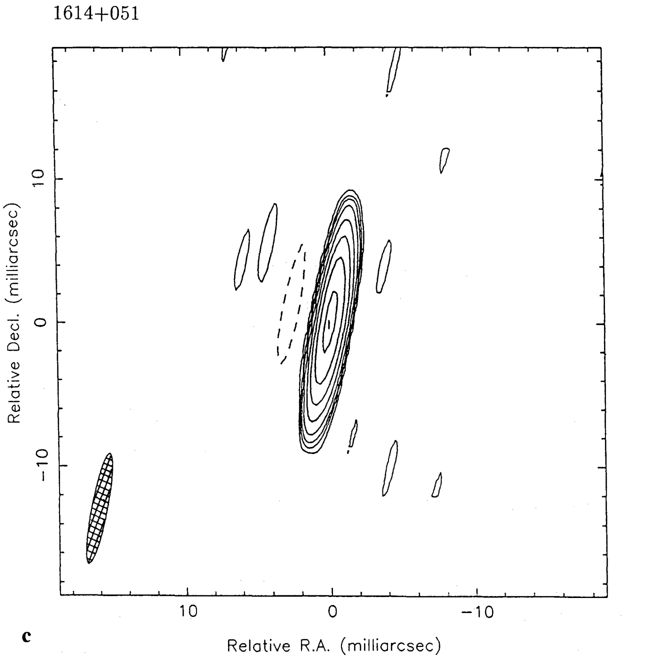


Fig. 3a–c. 5 GHz images of **a** 0642+449, **b** 1402+044, and **c** 1614+051. Contour levels: **a** −1, −0.4, 0.4, 1, 2, 3, 5, 10, 20, 40, 60, 80, 99% of the peak brightness, which is 888 mJy/beam; restoring beam is 2.2 × 0.73 mas in PA 0°. Stations: BFGKLOSW (see Table 4); date of observation: 24 September, 1987. **b** −0.5, 0.5, 0.75, 1, 1.5, 2, 2.5, 3.5, 10, 20, 40, 60, 80, 99% of the peak brightness, which is 619 mJy/beam; restoring beam is 10 × 2 mas in PA −2°. Stations: BGKLOSWY; date of observation: 21 November, 1986. **c** −0.5, 0.5, 1, 3, 5, 10, 20, 40, 80, 99% of the peak brightness, which is 605 mJy/beam; restoring beam is 7.7 × 0.95 mas in PA −11°. Stations: BFGKLOSWY; date of observation: 23 September, 1987

features, we do not place much reliance on details of substructure shown. The noise level in the maps is ~1.3 mJy/beam, giving dynamic ranges in the maps of typically 200 to 1.

Table 5

Source	Component	Flux density (Jy)	Separation (mas)	Position angle (°)
0642+449	A	0.9	0	0
	B	0.09	2.8	87
	C	0.09	4.3	77
	D	0.05	7.4	72
1402+044	A	0.6	0	0
	B	0.015	4.4	−102
	C	0.025	10	−42
	D	0.015	11.9	−56
	E	0.02	12.1	−82
	F	0.03	14.5	−90

4. Discussion

4.1. 0642+449

The spectrum of 0642+449 contains at least two components peaked at about 2 and 12 GHz, respectively (Fig. 1a). The higher frequency component is clearly variable (Altschuler & Wardle 1976; Kesteven et al. 1976; Wardle et al. 1981).

A few attempts to investigate the structure of the source on different scales and at different frequencies have been made. There is no evidence of extended structure in WSRT observations at 92 and 6 cm (de Bruyn 1991) on scales of 40 and 3 arcsec, at noise levels of ~1 and ~0.1 mJy, respectively. VLA observations at 20 and 6 cm (Perley 1982) give an upper limit for the peak brightness of any secondary structure of 0.3% of the peak of the primary component.

VLBI observations of 0642+449 have been made several times in the past (see Gubbay et al. 1977; Marscher & Shaffer

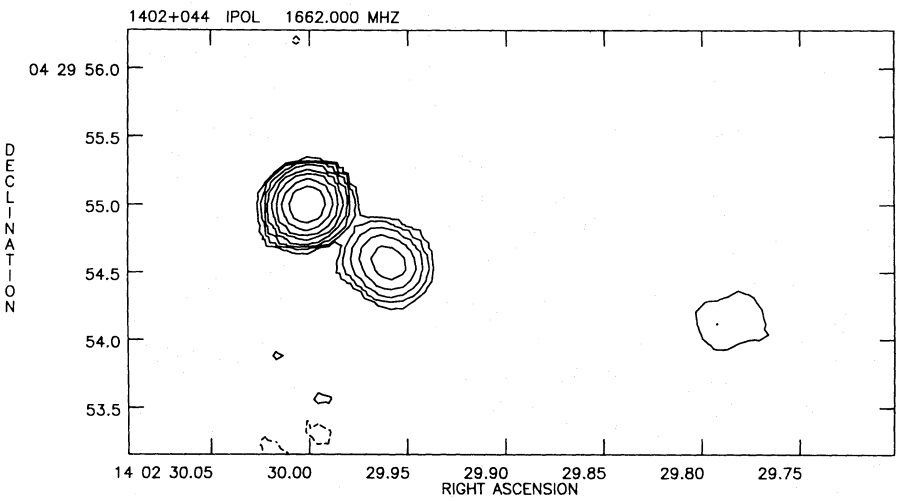


Fig. 4. MERLIN contour map of 1402 +044 at 18 cm. Contour levels are −1.5, 1.5, 3, 6, 12, 24, 48, 96, 192 mJy/beam. The restoring beam is 0.25 arcsec

1980; Preston et al. 1985) in the wavelength range 2.8–18 cm. Both Marscher & Shaffer (1980) and Preston et al. (1985) found evidence for structure on milliarcsecond scales, but neither had sufficient data to produce an image.

Figure 3a shows that 0642+449 has an extended non-linear structure which is characteristic of a jet (Bridle & Perley 1984). The peak brightness in the jet is ∼4% of that in the dominant unresolved component. The jet extends ∼8 milliarcsec to the east, which corresponds to ∼40 pc ($H_0=75$ km s^{-1} Mpc^{-1}, $q_0=0.5$). The jet appears to be distorted, with a maximum bending angle of ∼50°. The bending angle is defined as the angle through which the jet flow apparently rotates from one component to the next. The flux densities and relative positions of components in 0642+449 are given in Table 5.

4.2. 1402+044

VLA observations at 20 and 6 cm (Feigelson et al. 1984) do not resolve the source. MERLIN observations at 18 cm (Barthel & Lonsdale, unpublished; Fig. 4) show a secondary component at a separation of 0.8 arcsec to the south-west in position angle −123°. The flux density of this component at 18 cm is ∼30 mJy while that of the main component is 420 mJy. In addition, faint extended emission at 3.3 arcsec in position angle −106° is observed.

WSRT observations at 6 cm (de Bruyn 1991) which have a resolution of 3.5 arcsec in RA confirm the existence of the emission discovered with MERLIN. The secondary component seen by MERLIN contributes about 20 mJy at 6 cm, but there is also an additional 15 mJy component on the scale of 1–5 arcsec on the west side of the core.

Our VLBI data (Fig. 3b) show that 1402+044 also has an extended jet with a similar peak brightness relative to the dominant unresolved component as 0642+449. The jet extends ∼18 milliarcsec to the west (85 pc). Again, like 0642+449, the jet is distorted with a maximum bending angle (as defined above) of ∼90°. The flux densities and relative positions of the components in 1402+044 are given in Table 5. After the first kink, the jet (through components, C, D, E, and F) is roughly aligned with the kpc-scale structure seen on the MERLIN map (Fig. 4).

4.3. 1614+051

This source became well known by virtue of its companion – a probable galaxy at a very similar redshift to the QSO of 3.218 (Djorgovski et al. 1987 and references therein). Djorgovski et al. (1987) presented radio images of 1614+051 obtained from VLA A-array observations at 20 and 6 cm which show a double morphology with a secondary component located at a distance of 0.8 arcsec in position angle −30°. The primary component, which is identified with the optical QSO, has an inverted spectrum ($\alpha=0.8$) while the secondary component has a steep spectrum ($\alpha=-1$).

Our VLBI observations have a very elongated beam (HPBW $=7.7\times0.95$ mas) oriented in position angle −11°, which would mask compact structure on VLBI scales which may be aligned with the arcsec scale structure. In fact, the data on 1614+051 is well fitted by a circular Gaussian component of strength 0.75 Jy and size 0.8 milliarcsec.

5. Final remarks

Finally we wish to make two comments. We have already noted that both 0642+449 and 1402+044 have distorted jets. The angles through which the jets apparently swing are typical of core-dominated objects (e.g. 3C 345, Biretta et al. 1986), in which a small intrinsic bending is magnified by projection.

The second comment concerns an extrapolation of the relation between proper motion and redshift presented by Cohen et al. (1988): for sources at redshifts of 3.5, the proper motion values are expected to be around 0.012 mas yr^{-1} (empirically derived dependence) or 0.07 mas yr^{-1} (theoretical prediction, using $H_0=75$ km s^{-1} Mpc^{-1}, $q_0=0.5$, and $\gamma=5$). Thus unless the proper motion in these high-redshift objects is considerably greater than expected from standard cosmological models, it will be difficult to detect proper motion on timescales of a few years, even with the largest ground arrays. The planned space VLBI mission RADIOASTRON which will combine an element in space with the ground arrays will, however, be crucial to this study.

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