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Two new candidate superluminal quasars: 4C 28.45 and 4C 21.35

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Abstract. Multi-epoch VLBI observations are presented of two large double-lobed quasars, 4C 28.45 (1830+285) and 4C 21.35 (1222+216). On mas-scales, both quasars contain a multi-component asymmetric radio structure. In 4C 28.45 the nuclear emission was seen to expand, the observed proper motions corresponding to an apparent expansion velocity of $(3.0 \pm 0.8)c$. In the case of 4C 21.35, the evidence for superluminal motion is less strong; the data are compatible with an apparent expansion velocity of $(1.6 \pm 0.6)c$.

Key words: interferometry – quasars: general – radio sources: general – superluminal motion

1. Introduction

Extensive VLBI monitoring has resulted in the detection of superluminal expansion in the cores of more than 25 radio-loud QSO's and radio galaxies (see e.g. lists in Impey 1987; Cohen et al. 1988). Approximately one third of these objects possess extended radio emission on angular scales of several tens of arcsec or more. In this paper we present the results of new VLBI observations, indicating the presence of superluminal velocities in the nuclei of another two lobe-dominated radio sources, the quasars 4C 28.45 (1830+285) and 4C 21.35 (1222+216).

2. Observations and data reduction

In the context of a program to monitor the small scale radio structure in the nuclei of lobe-dominated quasars (Barthel et al. 1984; Hooimeyer et al. 1991a, b), the quasars 4C 28.45 and 4C 21.35 have been observed repeatedly with VLBI networks. Preliminary survey observations (Barthel et al. 1984; Hooimeyer et al. 1992a) indicated both objects to have a resolved radio structure on mas-scales. Subsequently, several follow-up observations of longer duration were made. A logbook of the observing runs is given in Table 1. All observations were carried out at 5 GHz with transatlantic networks, using the Mk II recording system at 1.8 MHz bandwidth. Left circular polarization was recorded.

Correlation of the data was carried out with Mk II correlator at the California Institute of Technology in Pasadena. Global fringe fitting was applied to the data of epochs 1988.24 and 1988.45. After correlation and fringe fitting, the data were coherently averaged over 2–4 min. To obtain an absolute flux density scale, observations of several calibrator sources were included in each run. Standard calibration procedures were applied (e.g. Cohen et al. 1975). The resulting absolute flux density levels are believed to be correct to within 5% for each observation. For the subsequent self-calibration and cleaning procedure, both the AIPS and the Caltech VLBI software packages were used. The noise level typically obtained in the maps is 1–3 mJy.

3. The quasar 4C 28.45 (1830+285)

The radio source 4C 28.45, also known as 1830+285, is associated with a 17^{m} QSO at a redshift $z = 0.594$ (Hewitt & Burbidge 1987). It has a classical triple radio structure with a largest angular size of 30 arcsec (Hintzen et al. 1983; Hooimeyer et al. 1991b). Adopting $H_0 = 100h$ km s^{-1} Mpc^{-1} and $q_0 = 0.05$ (used throughout), this corresponds to a projected linear radio size of $130h^{-1}$ kpc. The radio source contains a prominent, straight and clumpy radio jet extending to the hot spot in the northwestern lobe, and a fairly bright radio core containing roughly one third of the total source flux density at 5 GHz.

4C 28.45 has been observed three times with VLBI networks, in 1984.78, 1986.42 and 1988.45. The duration of the observing runs and the stations involved are listed in Table 1. The 1986.42 and 1988.45 observations each covered a full twelve hours, and yielded high quality data. The first epoch, 1984.78, was an observation from the snapshot survey, the results of which have been presented in Hooimeyer et al. (1991a). In this survey 4C 28.45 was observed at three intervals, for a total duration of $\sim 1\frac{1}{2}$ h. Although the uv-coverage of this experiment was limited, the data included several important maxima and minima in the correlated visibilities. This has resulted in a crude hybrid map displaying all the essential features observed in the 1986.42 and 1988.45 data. We will therefore use the 1984.78 map as a first epoch reference, even though it is not as reliable as the full-track data of 1986.42 and 1988.45.

Maps of the second and third epochs are shown in Fig. 1a, b. The nuclear radio emission consists of a typical core–jet structure, in which several components positioned close to one another can be distinguished. Most of the nuclear radio flux ($\sim 80\%$) is contained within the easternmost component A. This component, which is slightly resolved, is believed to represent the quasar core, both because of its relative strength and because of

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Table 1. VLBI observing log

Source	Obs. date	Duration (h)	Telescope network
4C 28.45	13/10/84 (1984.79)	2.5	SBWL-KO
	02/06/86 (1986.42)	12	SBWL-KGYO
	13/06/88 (1988.45)	12	SBWLJ-KGFYOP
4C 21.35	01/06/86 (1986.42)	6	SBWL-KGYO
	27/03/88 (1988.24)	12	SBWLJ-KGFYO

Station names: S = Onsala (26 m), B = Effelsberg (100 m), W = phased WSRT (14 × 25 m), L = Medicina (32 m), J = Jodrell Bank (76 m), K = Haystack (36 m), G = Green Bank (43 m), F = Ft. Davis (30 m), Y = phased VLA (27 × 25 m), O = Owens Valley (40 m), P = Pie Town (25 m).

its flux variability: between 1986.42 and 1988.45, when the total 5 GHz flux density of 4C 28.45 as measured by the Effelsberg telescope dropped from 1.15 to 1.00 Jy, component A decreased in flux density from 363 to 273 mJy, whereas the other components remained approximately constant in strength. Assuming A to be the core, the mas-scale structure in 1830+258 is pointing in the same direction as, and closely aligned to, the kpc-scale radio jet, the position angles of small and large scale emission being −37° and −42°, respectively. Such a close alignment between the VLBI emission and the kpc-scale radio jet is commonly observed in large double-lobed quasars (e.g. Hooimeyer et al. 1991a). A resolved jet-like structure is extended to the west of the presumed core component A. This feature contains at least two distinguishable sub-components, designated B and C. Additionally, the visibilities on the shortest baselines indicate that more diffuse emission is present at larger distances (∼30 mas) from the core. No emission above the noise level is present within a few mas to the east of A.

The positions of the various components in the two maps displayed in Fig. 1 have been determined in three ways: (a) by direct measurement from the maps, (b) by modelfitting of a few Gaussian components to the fringe visibilities, using both amplitude and phase information, and (c) by modelfitting to the visibilities, using the phase information only. Method (c) avoids systematic errors due to uncertainties in the absolute flux calibration. A weighted mean of the model component parameters derived in these three ways is presented in Table 2 for all three epochs. The quoted error values have been estimated from fits "by eye", and from the χ^2-values of the modelfitting procedure.

Components B and C appear to be receding from A. Using only the full-track maps of epochs 1986.42 and 1988.45, proper motions $\mu_B = (0.14 \pm 0.05)$ mas yr^{-1} and $\mu_C = (0.15 \pm 0.05)$ mas yr^{-1} are derived for components B and C, respectively. Including the model from the pilot survey of 1984.78, and performing a weighted least squares fit to the component separations, we find to within the errors the same results: $\mu_B^{(3)} = (0.13 \pm 0.04)$ and $\mu_C^{(3)} = 0.13 \pm 0.04$. At a redshift of $z = 0.594$ and using $H_0 = 100h$, $q_0 = 0.05$, these proper motion values correspond to apparent expansion velocities $v_B = (3.0 \pm 0.8)h^{-1}c$ and $v_C = (2.9 \pm 0.8)h^{-1}c$, respectively.

In the simple relativistic beaming model (e.g. Pearson & Zensus 1987), an average apparent velocity of $3c$ implies that the orientation of the mas-scale structure of 4C 28.45 must be within the angle $\theta_{max} = 38°$ of the line of sight. Minimizing the intrinsic flow speed, the inclination angle becomes $\theta_{min} = 19°$, and correspondingly $\gamma_{min} = 3.1$. Assuming an inclination angle θ_{min}, the deprojected linear radio size of 4C 28.45 would be $400h^{-1}$ kpc; as

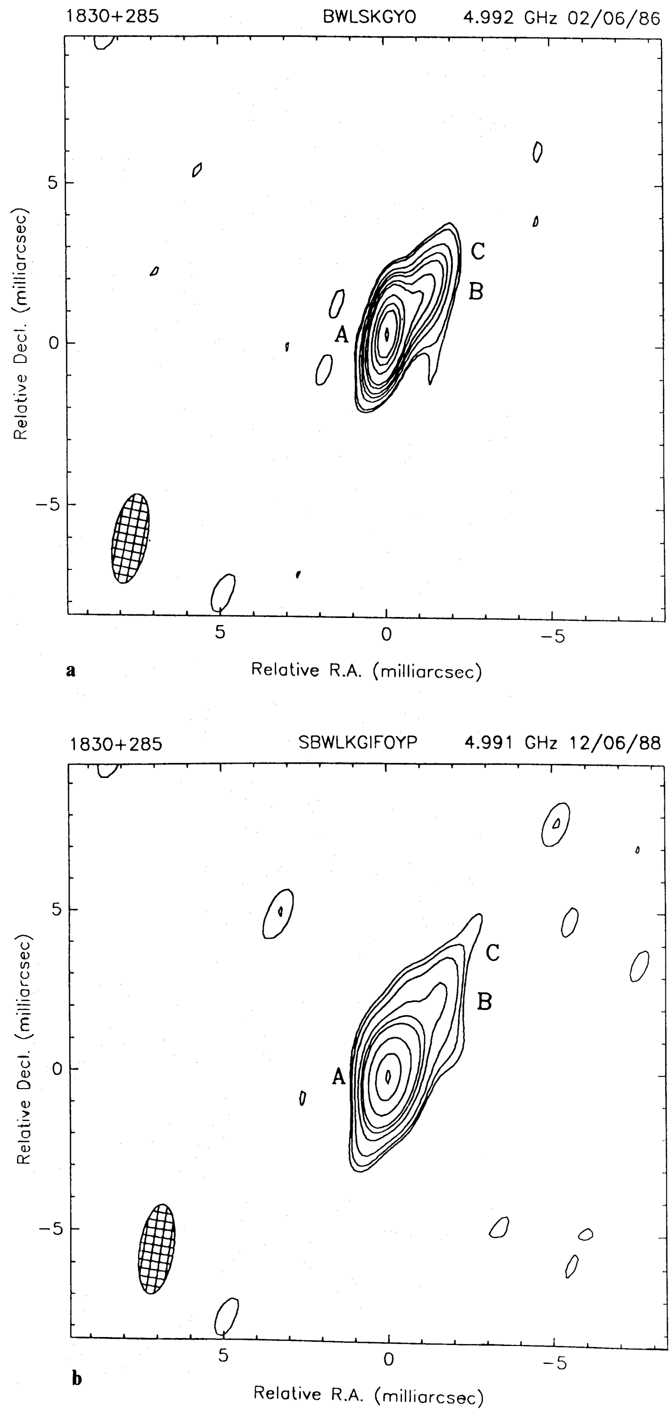

Fig. 1a and b. The total intensity distribution I for 1830+285 at epochs 1986.42 (**a**) and 1988.45 (**b**). In both cases the restoring beam is an ellipse of 2.8 × 1.2 mas, at a position angle of −5°. **a** Epoch 1986.42. Contour levels in the map are −1, 1, 2, 4, 8, 16, 32, 64 and 96% of the peak flux density level of 325 mJy/beam. **b** Epoch 1988.45. Contour levels in the map are −1, 1, 2, 4, 8, 16, 32, 64 and 96% of the peak flux density level of 228 mJy/beam

Table 2. Parameters of CLEAN model components for 4C 28.45

Epoch	Component	Flux (mJy)	Distance (mas)	p.a. (°)	Size (mas)
1984.79	A	303±2	0.00	0	0.5±0.1
	B	41±2	2.0±0.2	−33±2	0.3±0.1
	C	25±2	3.2±0.2	−38±1	0.5±0.1
1986.42	A	331±3	0.00	0	0.6±0.1
	B	25±2	2.1±0.1	−37±2	0.5±0.1
	C	21±2	3.9±0.1	−33±1	0.5±0.1
1988.45	A	299±2	0.00	0	0.8±0.1
	B	38±2	2.4±0.1	−40±2	0.6±0.1
	C	17±2	4.2±0.1	−35±1	0.6±0.1

such, it would be numbered among the largest superluminal objects known to us.

4. The quasar 4C 21.35 (1222+216)

The radio source 4C 21.35 (1222+216) is associated with a $17^{\mathrm{m}}.5$ QSO at a redshift $z=0.435$. It has a highly distorted radio morphology of ~ 17 arcsec in angular extent, which corresponds to a projected linear size of $\sim 65h^{-1}$ kpc. Strongly curved kpc-scale jet emission is present on both sides of the nucleus (Hintzen et al. 1983; Neff, private communication). At 5 GHz, the core contains roughly half of the total source flux density.

As with 4C 28.45, a preliminary survey (Barthel et al. 1984) indicated the presence of resolved structure on mas-scales in the core of 4C 21.35. Two follow-up observations of longer duration were carried out at epochs 1986.42 and 1988.24 (see Table 1). Both the quality and the quantity of the data on 4C 21.35 are inferior to those of 4C 28.45. The survey snapshot data (epoch 1981.27) were not sufficiently reliable to be used as a first epoch reference. The 8-station experiment of 1986.42 was carried out in source switching mode between 4C 21.35 and a nearby quasar from the same monitoring project; this resulted in significant gaps in the uv-coverage and a correspondingly less reliable hybrid map. The map of the highest quality was obtained from the 1988.24 data, which covered a full twelve hours and involved 10 stations.

The mas-scale radio structure of 4C 21.35 as derived from the 1986.42 and 1988.24 experiments is displayed in Fig. 2. Again, the nuclear emission is of "core-jet"-type. The southernmost component A, presumed to be the core, contains $\sim 85\%$ of the flux in the map. A resolved jet-like structure extends to the northwest, in the direction of the kpc-scale radio jet. No emission has been detected to the south or southeast of A. Small variations in the visibilities on the shortest baselines do indicate the presence of a slight amount of diffuse emission on scales of several tens of mas to the north of the core.

As was the case for 4C 28.45, source models for the two epochs of 4C 21.35 were constructed in three different ways: direct measurement from the maps, modelfitting of Gaussian components to amplitude and phase visibilities, and modelfitting to the phase data only. A weighted average of the results of the three methods for both epochs is presented in Table 3. The quoted error estimates have been derived as described above for the case of 4C 28.45. Due to the gaps in the uv-coverage, and to the lack of clear

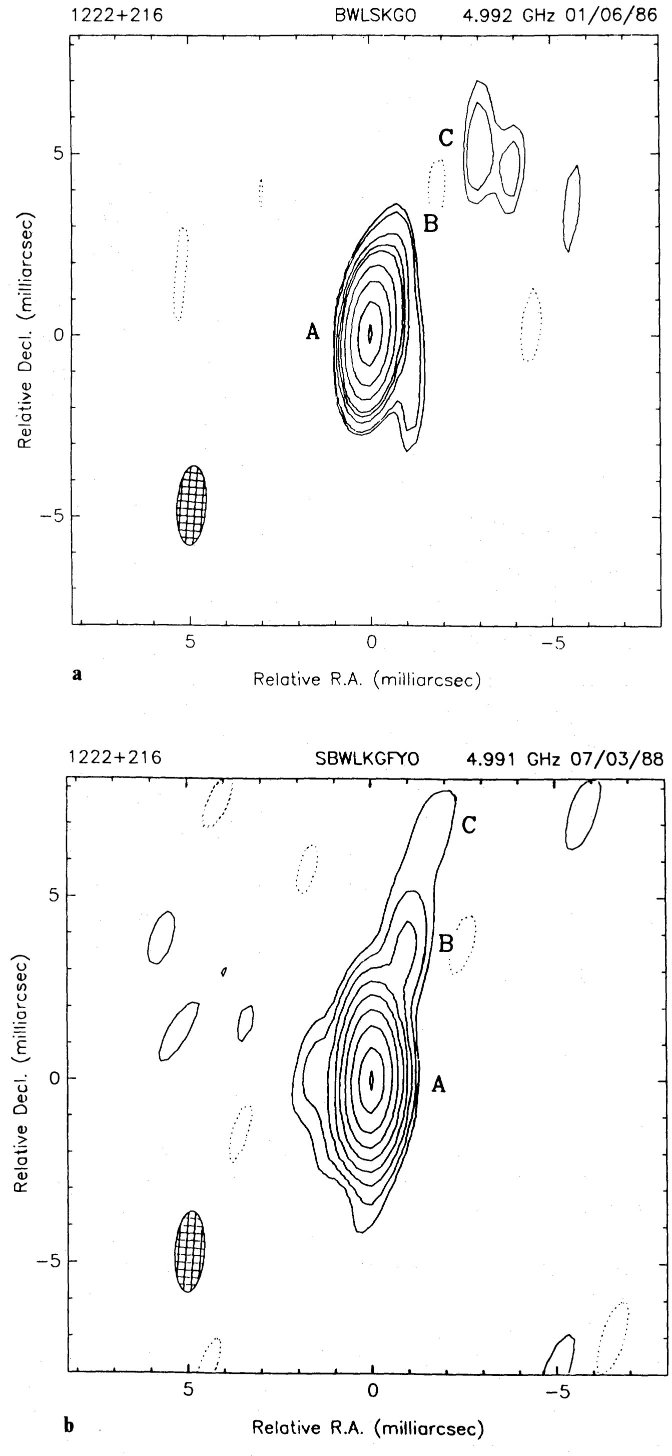

Fig. 2a and b. The total intensity distribution I for 1222+216 at the epochs 1986.42 (**a**) and 1988.24 (**b**). In both cases the restoring beam is an ellipse of 2.4×0.9 mas, at a position angle of −8°. **a** Epoch 1986.42. Contour levels in the map are −0.5, 0.5, 1, 2, 4, 8, 16, 32, 64 and 96% of the peak flux level of 352 mJy/beam. **b** Epoch 1988.24. Contour levels in the map are −0.5, 0.5, 1, 2, 4, 8, 16, 32, 64 and 96% of the peak flux level of 690 mJy/beam

maxima and minima in the visibilities, the data of 4C 21.35 offer less restrictions than those of 4C 28.45, and the error estimates are correspondingly larger.

Table 3. Parameters of CLEAN model components for 4C 21.35

Epoch	Component	Flux (mJy)	Distance (mas)	p.a. (°)	Size (mas)
1986.42	A	360 ± 3	0.00	0	0.8 ± 0.1
	B	18 ± 2	3.3 ± 0.1	-15 ± 1	0.8 ± 0.1
	C	7 ± 1	7.2 ± 0.1	-12 ± 1	0.8 ± 0.1
1988.24	A	691 ± 3	0.00	0	0.45 ± 0.02
	B	52 ± 2	3.5 ± 0.1	-14 ± 2	0.8 ± 0.1
	C	8 ± 1	7.2 ± 0.1	-14 ± 2	1.2 ± 0.1

Comparing the two epochs, several differences can be noted between the maps of epochs 1986.42 and 1988.24. Between 1986.42 and 1988.24, the flux of the radio emission of 4C 21.35 increased by more than 70%. In this time interval, component A nearly doubled in intensity and became somewhat resolved; the other components remained roughly constant in flux density. The diffuse, resolved feature C observed in the 1988.24 map, is not present above the noise level in the 1986.44 data.

The secondary component B has receded from A in the period 1986–1988. In the 1.73 years separating both observations, the distance between features A and B has increased by 0.16 ± 0.09 mas, implying a proper motion $\mu_B = 0.09 \pm 0.04$ mas yr^{-1}. At $z = 0.435$ this value corresponds to an apparent expansion velocity $v_{appB} = (1.6 \pm 0.6)h^{-1}c$. At this moderate velocity, minimizing the Lorentz factor γ would imply for 4C 21.35 a jet inclination angle $\theta_{min} = 32°$, $\gamma_{min} = 2.0$, and a deprojected linear radio size of $\sim 130h^{-1}$ kpc. These are all fairly typical values for extended superluminal quasars.

5. Discussion

In the preceding sections, multi-epoch VLBI observations have been presented of two new candidate superluminal sources, the quasars 4C 28.45 (1830+285) and 4C 21.35 (1222+216).

In the case of 4C 28.45, the evidence for the presence of superluminal motion is strong. Self-consistent results have been obtained for three epochs and two components with measurable proper motions. A third full-track observation will be required to confirm the observed expansion of the nuclear components and to determine the component proper motions more accurately. Based upon the present results, 4C 28.45 presents us with yet another example of superluminal motion occurring in the nucleus of a large classical triple radio source. With its estimated deprojected radio size of $400h^{-1}$ kpc, it is located at the top end of the quasar linear size distribution (see Barthel et al. 1986). The derived velocity $(3 \pm 1)h^{-1}c$ is significant but moderate, as is commonly seen in lobe-dominated superluminals with nearly linear overall radio morphologies (e.g. 3C 179, Porcas 1987; 3C 263, Zensus et al. 1987; 1721+343, Barthel et al. 1989); in extended sources with more curved kpc-scale emission, such as 0850+581 (Barthel et al. 1986), 1642+690 (Pearson et al. 1986) and 1928+738 (Eckart et al. 1985) the observed expansion velocities are generally somewhat higher.

With its relatively small radio size and highly distorted jet (Hintzen et al. 1983), the kpc-scale radio structure of 4C 21.35 conforms more closely to the classical beaming picture of a superluminal source. Both the quality and the quantity of the data on 4C 21.35 are much inferior to those of 4C 28.45. The uncertainties in the positions of the various components are correspondingly larger. The data can therefore offer no more than an indication of superluminal expansion. Further observations must be made to confirm the reality of superluminal velocities in this quasar nucleus.

In conclusion, we feel that there is sufficient evidence to have confidence in the reality of superluminal motion in the core of the quasar 4C 28.45, at apparent velocities close to $3c$. In the case of 4C 21.35, the available data indicate observable proper motion and the presence of superluminal velocities, but they are of insufficient quality to establish this definitely.

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